mann a phyllite. Major Brooks himself designates it as a "light bluish gray, shining *clay slate*, with strong cleavage and no distinguishable bedding planes."[1] It does not belong to the rocks now especially under consideration, but since it was studied carefully it may be described here for comparison. This slate occurs in a bed, estimated by Brooks to be 550 feet in thickness, on both sides of the river and in its bed. It strikes nearly east and west and dips toward the north. In Brooks's collection this rock bore the number 2075; in the present collection it is represented by No. 11152.

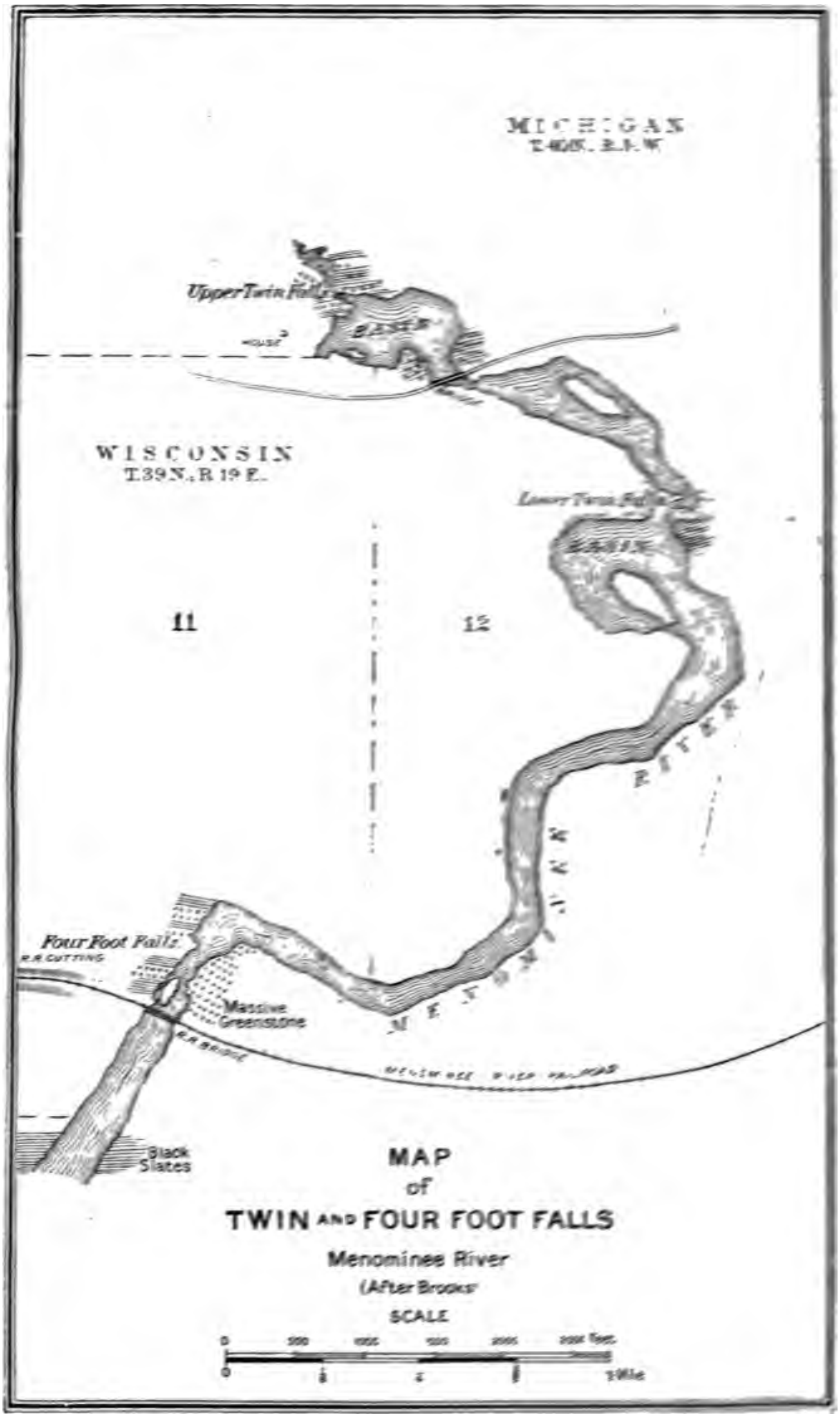
Under the microscope there are visible in the thin section of this specimen unmistakable signs of sedimentary origin. Coarser and finer areas alternate, the former being made up of clastic quartz grains, either pure or mixed with iron hydroxide or chlorite, while the latter are composed of an argillaceous substance, filled with extremely minute muscovite or sericite scales and considerable carbonaceous matter. Tourmaline needles are also occasionally seen; and zircon too, either in minute, whole crystals or as irregular fragments of larger ones, is not infrequent. This rock belongs to the detrital iron-bearing series, the boundary between which and the greenstone schists lies just above this exposure.

The railroad which crosses the bridge at Four-foot Falls exposes this same rock again in a cutting about a mile west of Iron Mountain. A specimen from this locality, No. 11114, shows the same general character as the last described rock, except that it is more crystalline. Tourmaline is present as before, but a new crystallization of biotite has largely replaced the chlorite. The carbonaceous material is less abundant and what remains is in a much more finely divided state. The clastic origin of the rock is still very apparent in the shape of its quartz grains, which are here mingled with feldspar fragments, both plagioclase, microcline and orthoclase.

No. 11113, from a quartzite band intercalated in No. 11114, also contains feldspar grains mingled with the quartz. Zircon fragments are likewise present and a little biotite, which is no longer quite fresh. This latter mineral shows in a beautiful manner the development of secondary rutile needles, as in the kersantites.[2]

Before speaking of the greenstones which occur along the river farther north, it will be well to examine those exposed in the railroad cutting at the western end of the bridge. These rocks are, for the most part, massive, but they nevertheless display evidence of extensive crushing and chemical alteration. No. 11178 represents the average type. This is of a light green color, and in a hand-specimen quite aphanitic. Both macroscopically and microscopically it resembles the massive greenstones so abundant in and representative of the region south of Marquette (see Pl. X, fig. 2). Mineralogically there is hardly a trace of the original rock left. Almost colorless hornblende, pale

[1] Geol. Wisconsin, vol. 3, p. 475.
[2] Rosenbusch: Mikros. Physiog., 2d ed., vol. 2, p. 311.



MAP
of
TWIN AND FOUR FOOT FALLS
Menominee River
(After Brooks)

Cat.

UNITED STATES GEOLOGICAL SURVEY

J. W. POWELL, DIRECTOR

THE GREENSTONE SCHIST AREAS

OF THE

NOMINEE AND MARQUETTE REGIONS OF MICHIGAN

A CONTRIBUTION TO THE SUBJECT OF DYNAMIC METAMORPHISM
IN ERUPTIVE ROCKS

BY

GEORGE HUNTINGTON WILLIAMS

WITH AN INTRODUCTION BY

ROLAND DUER IRVING

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OFFICE

Dr. J. C. Branner
with the sincere regard 28095
of G.H.Williams

DEPARTMENT OF THE INTERIOR

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BULLETIN

OF THE

UNITED STATES

GEOLOGICAL SURVEY

No. 62

THE GREENSTONE SCHIST AREAS OF THE MENOMINEE AND MARQUETTE REGIONS OF MICHIGAN

WASHINGTON
GOVERNMENT PRINTING OFFICE
1890

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LETTER OF TRANSMITTAL.

UNITED STATES GEOLOGICAL SURVEY,
LAKE SUPERIOR DIVISION,
Madison, Wisconsin, February 10, 1888.

SIR: I have the honor to transmit herewith, for publication as a bulletin of the Survey, a paper, by Prof. George H. Williams, of Baltimore, Maryland, on The Greenstone-Schist Areas of the Marquette and Menominee Regions of Michigan.

The exact object and bearing of the work thus accomplished by Prof. Williams I have set forth in an explanatory and historical note prefixed to his memoir.

I am, sir, very respectfully, yours,

R. D. IRVING,
Geologist in Charge.

Hon. J. W. POWELL,
Director U. S. Geological Survey.

EXPLANATORY AND HISTORICAL NOTE.

By Roland Duer Irving.

At quite a number of points in the Lake Superior region occur peculiar schistose rocks, which combine with a prevalent fine grain a general tendency to greenish color. Besides occurring here and there more or less confusedly mingled with masses of granite and other rocks, these greenish schists occur also in large continuous areas, which they entirely occupy, except for certain relatively unimportant basic and acid intrusives. Microscopic study has shown that these rocks are at times fully developed hornblende schists, and again glossy kinds, in which chlorite is so important an ingredient as to warrant our calling them chlorite schists. In other places again they are more massive, and present more or less distinctly the appearance of fine-grained basic eruptives; but the bulk of these areas is composed of nondescript fine-grained greenish schists, which appear to grade into the more massive greenstone-like forms on the one hand, and into the more distinctly developed chloritic and hornblendic schists on the other. As a rule these various schists present no parallel structure other than that which seems referable directly to secondary causes; that is to say, they do not present such banded varieties as would suggest the action of sedimentation during their production. However, such banded varieties do occur in subordinate quantity, presenting then very strikingly regular, rapid alternations of light and dark bands.

Again, here and there in these peculiar areas, in some places with a very considerable development, there occur kinds which present a more or less obscure fragmental appearance, this appearance being generally far more pronounced on a weathered surface than on a fresh one, on which latter the matrix and the parent fragments are apt to look much like one another, either from original similarity in character or from having undergone alterations which have led both fragments and matrix, originally different, to similar results. At times there is a coincidence of occurrence between the banding above referred to and the appearance of the pebble-bearing forms, but so far as my experience goes this is very commonly not the case, the fragmental phases being without any parallel structure other than the general secondary cleavage, which all of these rocks present, the apparent pebbles occurring more commonly in tumultuous assemblages of masses of all sizes.

As prominent illustrations of such green schist areas, there may be mentioned that which runs directly westward from the shore of Lake Superior at Marquette, Michigan, for a distance of some twenty miles, with a width ranging from two to six miles;[1] those which occur in the Menominee Valley, on the boundary between Wisconsin and Michigan;[2] that of the Gogebic country of western Michigan, in T. 47 N., R. 43 W., and T. 47 N., R. 44 W., where there is a very great development of the fragmental phases;[3] that which has been recently outlined by Dr. W. S. Bayley to the south of the so-called Mesabé Range, and west of the Embarras Lakes, in T. 59 N., R. 15 W., and T. 59 N., R. 16 W., northern Minnesota, where there is again a considerable development of the fragmental forms;[4] and that which lies to the northward of the iron-bearing slates of Vermillion Lake, traversing the island in the northern part of that lake from west to east, and extending thence east and northeast, with an average width of from two to three miles, through townships 62, 63, 64, and 65 N., of ranges 14, 13, 12, 11, 10, and 9 W., in northern Minnesota, to the national boundary line at Carp Lake, whence it extends an unknown distance into Canada. This last-named area, which is the most extended continuous one with which I am acquainted, shows prevalently those kinds of rock which lack the fragmental appearance. Still, fragmental phases here and there present themselves, as, for instance, along the east shore of that island in Vermillion Lake, which lies in the northern part of Sec. 10 and southern part of Sec. 3, T. 62 N., R. 16 W. To these areas may be added also several smaller ones which lie southward and southeastward of the Vermillion Lake iron belt. One of these areas, lying south of Sea Gull Lake and east of Ogishkimanissi Lake, in T. 65 N., R. 5 W., presents an extraordinary development of the obscurely fragmental or brecciated phase. Finally, should be mentioned the large development of similar greenish schists, including also the fragmental or "agglomeratic" phases, which is described as occurring on the Lake of the Woods in the recent report of Mr. A. C. Lawson, of the Canadian Survey.[5]

My first acquaintance with any of these green schist areas was in the summer of 1883, when a number of days were spent in examining the exposures at Twin Falls, Upper Quinnesec Falls and Lower Quinnesec Falls, on the Menominee River, the boundary between Wisconsin and Michigan. The very handsome detailed maps and the descriptions of these exposures by Maj. T. B. Brooks[6] had already been published and

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[1] See map of T. B. Brooks, Geol. Survey Michigan, Atlas, Pl. III; map by C. Rominger, accompanying Geol. Survey Michigan, Vol. 4, 1881; Pl. I of the present volume.

[2] See map by T. B. Brooks and C. E. Wright, Pl. 28 of the atlas to the Geology of Wisconsin; map by C. E. Wright, Pl. 30 of the same atlas; map of the Menominee region, by C. Rominger, Geol. Survey Michigan, Vol. 4, 1881, Pl. 2.

[3] See maps by R. D. Irving and C. R. Van Hise, accompanying a memoir on the Penokee-Gogebic iron region, Mon. U. S. Geol. Survey, No. 18.

[4] See map by R. D. Irving, Pl. XLI, of the Seventh Ann. Rept. U. S. Geol. Survey.

[5] See Geol. Nat. Hist. Survey Canada, Ann. Rep. (new series) Vol. 1, 1885, pp. 41-46 cc; also map accompanying same.

[6] Geol. Wisconsin, vol. 3, 1880.

were used on the ground. These maps represent the exposures at the several points named as composed of a series of very regular alternations of various schistose and massive rocks, the conclusion being reached with regard to them by Brooks that they form in all a regular series of layers originally of sedimentary origin, the present lack of fragmental appearance being taken as the result of metamorphism. To me it seemed at that time that the regularity of the alternations was far less than one would think to be the case from Brooks's maps, and that all of the several phases, schistose and non-schistose, were rather variations of one great mass of material, whose original structure was massive rather than schistose. This impression was gathered from the way in which the several phases graded into one another, and from the non-continuity in the direction of the strike of the schistose kinds, single schist beds displayed on one side of the stream being often absent where their continuations should lie on the opposite side of the stream. The impression was strengthened by the lack of regularity in the direction of the schist planes, and by the striking way in which schist bands inclose vaguely outlined areas of non-schistose massive rocks. The same conclusion as to the inseparable nature of all of these rocks had already been reached and published by Rominger,[1] though he appears to have looked upon the parallel or schistose structure as representing an original condition of the rocks, all of which he seems to consider of sedimentary origin; while the impression made on me was just the opposite, namely, that the schistosity is of a secondary nature, and the original structure of the rock a massive one. In order to test this question, a large collection of specimens, with quite full notes, was made at the time. In the next year, however, before the thin sections made from these specimens could be examined, the entire collection was destroyed by fire, and my work in other directions having become pressing, it was decided to put the study of this question in the hands of Prof. George H. Williams, of the John Hopkins University, whose qualifications for investigations in microscopic petrography, such as this would mainly be, are well known to be of the first order. In the summer of 1885, therefore, Professor Wllliams made, at my request, a reexamination of all of these points in the Menominee valley, going into far greater detail in the field study than any one had done before, and collecting on a very large scale. During the summer of 1886, Professor Williams was asked to extend his field examinations into the Marquette greenschist area, and here similar detailed studies and large collections were made. The present publication is the result of Professor Williams's work, which has included the detailed examination of about 400 thin sections made from the specimens gathered.

While Professor Williams's investigations have been going on, the various other green schist areas named, so far as they lie within the

[1] Geol. Survey Michigan, vol. 4, 1881, p. 214.

boundary of the United States, have been examined in considerable detail, large collections and extensive field-notes having been gathered by Prof. Van Hise, Messrs. W. N. Merriam and W. S. Bayley, and myself. These additional collections are now quite thoroughly sectioned, and it is hoped soon to study them in detail, and to offer a second contribution to our knowledge of this important class of rocks. The present publication, however, deals only with the Marquette and Menominee areas.

Prof. Williams's investigations having been directed especially to a microscopic study of these peculiar greenschists, with the object of ascertaining whether such study would throw any light upon their original condition; it does not come within the province of his memoir to discuss the geologic relations of the green schist masses as wholes. Nevertheless, it is almost unavoidable that some reference should be made in this volume to these geological relations, and, since there has been a good deal of difference of opinion as to them among the several geologists who have written upon the Menominee and Marquette areas, it seems necessary to explain briefly the different views that have been advanced, including the conclusions to which my own studies have thus far led me, though without attempting any general discussion of the subject for the whole Lake Superior region. Such a discussion it is designed to leave until exhaustive microscopic studies, like that of Professor Williams here presented, shall have been extended over the other areas of similar rocks above named. We shall then be in possession not only of all available structural facts with regard to these peculiar rocks, but also of all that the most refined methods of study can give us with regard to their internal texture and mineralogical composition.

The map (Pl. I) shows, in a general way, the distribution of the different kinds of rocks in the vicinity of Marquette. In preparing this map, those by Brooks and Rominger, read in the light of my own studies in this region, have been used. It should be said that a detailed map of the Marquette district has not been attempted by the U. S. Geological Survey as yet, partly because other more pressing work was in progress, and partly because without a thoroughly accurate topographical basis for such a map it has not been thought that much advance could be made upon the several maps heretofore constructed. It is proposed, however, to begin such topographical survey immediately, and upon the basis thus prepared, to place everything exactly as it is seen, and, making use of all the latest mining developments, to attempt to work out accurately and in detail the structure of the region in such a fashion that what is inferred may be easily separated from what is actually known.

Upon the present map the large area colored for greenstone schists is the one which came particularly under Professor Williams's investigations. Northward this area is limited, in the eastern portion, by a great spread of granitic and gneissic rocks. The line of demarkation between the schists and the granites, however, is not a sharp one, since the

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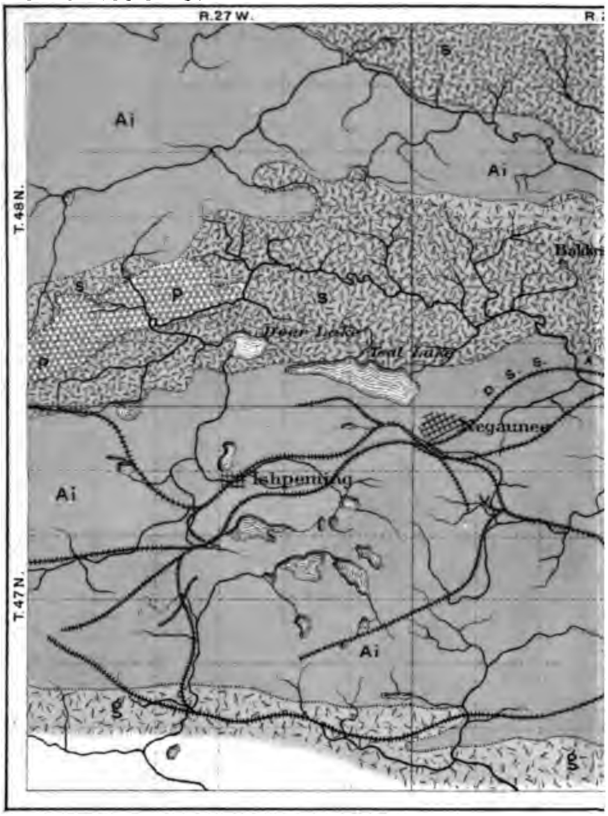

ARCHEAN. AGE UN

Granite and Gneiss. Greenstone Schists. Altered R

OUTLINE GEOLOGICAL MAP

Compiled by R.D.Irving from maps

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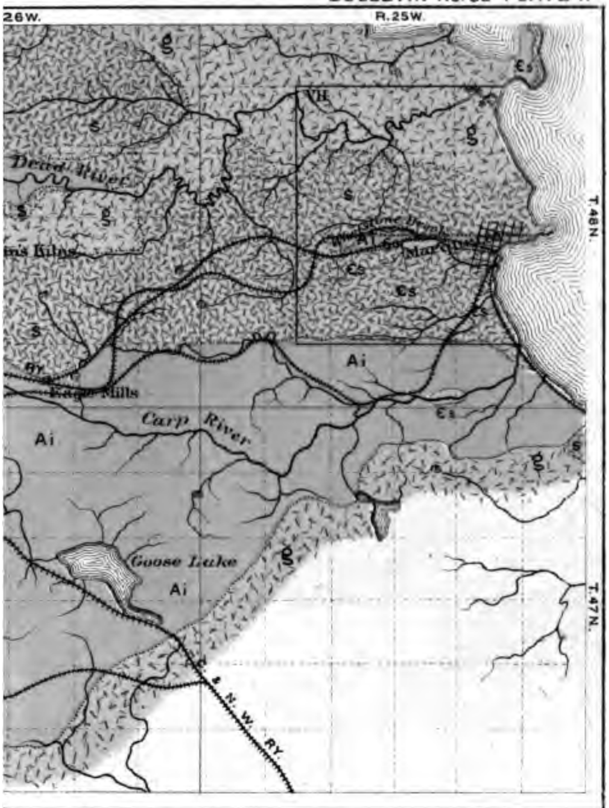

IKNOWN. ALGONKIAN. CAMBRIAN.

Peridotite. Iron Bearing Series. Lake Superior S.S.

(Detritals, Limestones and Ferruginous Schists, with interbedded Greenstones.)

Ai Ɛs

OF THE MARQUETTE REGION.

s by T.B.Brooks and C.Rominger.

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two seem to mingle more or less confusedly on each side of the somewhat arbitrary line indicated upon the map. Southward of this greenstone-schist area, and again dovetailing into it on the north, are belts of country occupied mainly by detrital rocks, such as quartzites and various fragmental slates; with these, however, are large bodies of crystalline limestone and several phases of ferruginous schist, all of which have in common an entire lack of anything like a fragmental texture. In addition to these rocks these areas include also sheets of diabasic greenstone, which are interbedded with the detritals and ferruginous schists alluded to. On the south of the southernmost of these detrital areas, in which are included all the well known iron mines of the Marquette region, is again a large area of granitic and gneissic rocks.

The greenstone schists are affected generally by a vertical or nearly vertical cleavage structure, to which the occasional banding of the rock, suggestive of a sedimentary origin, is also parallel. The layers of rock of which the detrital areas are composed are affected partly by a similar cleavage structure, but, on the whole, far less markedly so, while the bedding of these rocks is as a rule very distinct, and indicates a more or less open or gentle bowing of the layers, the dips being at times southward and again northward, and usually at a much lower angle than is the cleavage structure of the greenstone schists. At times, however, particularly in the easternmost portion of the southern of these two belts, the inclinations of the detrital rocks are much higher, and then bedding and cleavage structure approach to parallelism with each other, and with the cleavage structure of the greenstone schists further north. While folded back and forth, these detrital areas show for the most part an evident general synclinal structure; that is to say, the layers of rock of which they are composed, as they appear along the edges of these areas, dip inward towards their middle portions. Thus the greenstone schists seem plainly to rise from beneath the higher detrital layers. As to the inferior position of these greenstone schists to the detrital iron-bearing rocks, all geologists who have examined this region would probably agree; at all events all those who have expressed themselves with regard to the matter seem to have no hesitation concerning it.

Foster and Whitney, whose classical work[1] gives the first comprehensive account of the geology of this region, do not appear to have separated the greenstone schists from the other stratiform rocks in such a fashion as to indicate their exact stratigraphical relations. All of these stratiform rocks they appear to have looked upon as constituting one great series, whose crumpled condition they attributed to the subsequent eruption of the granite masses on either side of the single trough, which they regarded the stratiform rocks as occupying.[2] They

[1] Report of the geology of the Lake Superior land district, by J. W. Foster and J. D. Whitney, pt. 2. The Iron Region, Washington, 1851.

[2] Ibid., p. 41, Fig. 5.

appear, however, to refer especially to the greenstone schists in the following:

Many of the slates appear to be composed of pulverulent greenstone, as though they might originally have been ejected as an ash, and subsequently deposited as a sediment, and pass by imperceptible gradations, from a highly fissile to a highly compact state. * * * The slates are composed essentially of the same ingredients as the trappean rocks with which they are associated, and the main difference between them may be that the one was the product of salses, ejected in the form of mud, while the other was the product of volcanoes, ejected in molten streams.[1]

They appear also to refer especially to the greenstone schists when they speak of the stratiform series as exhibiting greater alteration in the vicinity of the masses of eruptive granite, than at distances from these masses.[2]

J. P. Kimball, who wrote in 1864,[3] considered the granitic and gneissic masses on either side of the belt of stratiform rocks, as corresponding to the Laurentian series of Canada, while he parallelized the whole of the stratiform succession with the Huronian series of the north shore of Lake Huron, thus making the granitic and gneissic rocks the older basement upon which all of the stratiform Huronian was subsequently spread, wholly by aqueous agencies. None of the various rocks which Foster and Whitney looked upon as eruptive, are thought by Kimball to have had that origin, even the various greenstones being taken to be metamorphic sedimentary material. In the case below Kimball appears to refer particularly to the greenstone schists, which form our present subject, and which, it thus appears, he looked upon as the basement member of the Huronian succession. He says:[4]

The gneiss which marks the boundary of the granite belts, and accordingly characterizes the top of the Laurentian series in this region, the same as it is elsewhere represented, is succeeded by dark colored hornblendic schists, which consequently represent the base of the Azoic or Huronian series. These schists are followed by a series of augitic rocks and schists, interstratified with magnesian hydrous rocks and slates, the two kinds of rocks being represented on the one hand by hypersthene, pyroxene, and bedded diorite passing into dioritic slates, and on the other by talcose and chloritic schists. The former character of rocks prevails to such an extent as to impart to the lower members of the Huronian series a distinctive augitic aspect. The several rocks composing this augitic zone are commonly of a greenish color, and vary in this respect chiefly as to shade, resembling in this particular the Lower Slate Conglomerate, which marks the base of the series in Canada, and from which they seem to differ only in the absence of pebbles and bowlders from the subjacent Laurentian rocks, which there form a distinguishing feature.[5]

[1] Report of the geology of the Lake Superior land district, by J. W. Foster and J. D. Whitney, pt. 2. The Iron Region, Washington, 1851, pp. 16, 17.

[2] Ibid., p. 14.

[3] Am. Jour. Sci., 2d series, vol. 39, 1865, pp. 290–303.

[4] Ibid., p. 294.

[5] This supposed similarity of the greenstone schists of Marquette to the Lower Slate Conglomerate of Lake Huron is not borne out at all by later microscopic and field studies. Indeed, the two have nothing whatever in common, unless the occasional greenish color of the Lake Huron rocks be taken to indicate such a resemblance. The Lower Slate Conglomerate of Lake Huron, with its granitic and gneissic pebbles, proves to be a most completely detrital and plainly water-formed mass composed chiefly of fragments of quartz and feldspar, with the alteration products of the latter, the whole cemented by [illegible]ous paste. This statement is made only after a careful examination of the Lake Huron region, [illegible] the study of a very large number of thin sections from Logan's so-called Lower Slate Con[illegible]ate.

T. B. Brooks, upon his detailed map of the Marquette district[1] leaves blank the larger part of the area occupied by the greenstone schists which now especially concern us, indicating here and there upon it, however, the occurrence of belts of "diorite" and of "chloritic and dioritic schists." All of these rocks he evidently regards as belonging conformably beneath the detrital quartzites and slates which form his division No. V, of the iron-bearing series, which division appears in a bold ridge along the northern edge of the southern of the two detrital areas indicated on the outline map herewith. The diorites Brooks classes lithologically with the greenstones interstratified with the detrital rocks themselves, though apparently looking upon them as belonging to much lower layers in the succession. In this lithological correlation, as will be seen in the sequel, Brooks was largely correct, since the diorites of the greenstone schist area prove to be diabasic greenstones in dike form, and to be entirely similar lithologically to the interbedded greenstones of the detrital or iron-bearing areas, with which they are also presumably wholly contemporaneous. All of these rocks, both massive and schistose, Brooks plainly regarded as metamorphosed water-formed sediments.

Wadsworth, writing in 1880,[2] advocates in the main the views presented by Foster and Whitney, as will be seen by the following quotation:

> The general structure of the country would seem to be as follows: The schists, sandstones, etc., having been laid down in the usual way, were then disturbed by the eruption of the jasper and ore; this formed the knobs of jasper, the banding belonging to the fluidal structure, and not to sedimentation. Besides occurring in bosses, the jasper was spread out in sheets, and intruded through the rock in wedge-shaped masses, sheets, and dikes. Much of the original rock still remained horizontal, and new sedimentary deposits continued to be formed out of the jasper and the other rocks. Next came the eruption of "diorite," which completed most of the local folding and tilting of the strata. Finally, the granite eruption took place on both sides of the "Huronian," uplifting and contorting the strata near it, and perhaps laterally compressing the inclosed iron-bearing rocks.[3]

Dr. Wadsworth does not appear to express any particular opinion as to the stratigraphical position of the greenstone schists of the area now especially under consideration, speaking of them only in connection with all the rest of the stratiform rocks of the region as older than the adjacent granite areas. The greater part of these greenstone schists he would seem to have looked upon as certainly sedimentary,[4] since he records a number of observations going to show that there is no gradation between them and certain dike-like masses occurring with them, using these observations in opposition to the ideas expressed by some of his predecessors to the effect that inasmuch as the massive rocks and

[1] Geol. Survey, Michigan, 1873, vol. 1, Atlas pl. 3. See also pp. 99–104, same vol.

[2] Notes on the Geology of the Iron and Copper Districts of Lake Superior. By M. E. Wadsworth Bull. Mus. Comp. Zool. Harvard College, Whole Series, vol. 7 (Geol. Series, vol. 1 No. 1).

[3] Ibid., p. 75.

[4] Ibid., p. 37.

the schists grade into one another, the former are of sedimentary origin as well as the latter. That there are genuine dikes intersecting these schists and having no gradations into them, Professor Williams's observations recorded in this volume, as well as those by Rominger and others, make very plain, although even in the case of these genuine later dikes there are at times partially schistose forms produced apparently by secondary dynamic agencies. On the other hand, it will be seen from Professor Williams's descriptions that there are other massive forms among these greenstone schists which do present every possible gradation into the schists themselves, and must, therefore, be believed to have had a common origin with them.

Rominger, in his account of the geology of the Marquette region, published in 1881,[1] describes very fully the greenstone-schist area which Professor Williams has studied. Rominger's mapping of this area has essentially been followed upon the small sketch-map accompanying the present volume. The rocks of this area he describes under the general head of the "dioritic group," which group he looks upon as forming the basement member of the Huronian series within which he would include all the stratiform rocks of the region, considering it as placed conformably beneath the detrital strata. The origin of the structure of these greenstone schists he looks upon as having been a secondary one, although he recognizes distinctly their intrusion by later genuinely eruptive dikes. Inasmuch as in its more northern portion the greenstone-schist area presents numerous bosses and veins of granite, he considers these as proving the more recent origin of the great granite masses lying both to the north and south of all stratiform rocks, thus returning, as did Wadsworth before him, to the early expressed view of Foster and Whitney, with whom he agrees also in considering that the crumpling of all of the stratiform rocks, greenstone schists and detritals as well, has been accomplished by the protrusion of the later granite masses on either side. In the same volume, and upon his map, Dr. Rominger indicates numerous small areas of massive and schistose greenstones as occurring in the vicinity of Negaunee and Ishpeming, within the district represented on the outline map herewith, as occupied entirely by the detrital iron-bearing series. These masses he regards as forming portions of his dioritic group, although at the same time recognizing distinctly the fact that they occur at various horizons among the detritals, which he looks upon as lying wholly above the main mass of his dioritic rocks. This anomalous arrangement he explains by representing that the dioritic group, inasmuch as it lies at the base of the entire stratiform series, comes directly into contact with the granite protrusions, whose metamorphosing influence was so great as to cause the fusion of a portion of these basement layers. These fused portions, then, he imagines to have intruded themselves in various shapes among the higher detrital layers.[2] This view, how-

[1] Geol. Survey Michigan, 1881, vol. 4, with map of Marquette region.
[2] Ibid., pp. 22-39, particularly pp. 37, 38.

ever, Dr. Rominger subsequently abandoned, as will appear from the following quotation from the manuscript of his last and yet unpublished report:[1]

> As from the massive form of the diorites a gradation exists into the schistose condition, and as schistose structure formerly appeared to me a positive proof of a former sedimentary origin, I resorted in my previous report, in order to explain the similarity in the composition of the schists with the massive diorites, to the hypothesis of a secondary fusion of the lower beds of sediments nearest to the focus of central heat, and subsequent injection of the fused part into the folds and fissures of the remainder of the strata, simultaneously also the molten mass to have been forced into the fissures and crevices of the adjoining granite. I have since lost much of my faith in this supposition, since I have convinced myself that schistose structure is not necessarily the result of aqueous sedimentation, but that cooling eruptive masses under circumstances can assume a schistose form. * * * I am inclined to suppose that these schists so intimately associated with massive diorite beds are a product of their decomposition, under circumstances favoring the schistose arrangement of the molecules, or, to speak in more definite terms, are a modified form of these eruptive masses, and do not refer to former sedimentary deposits.

My examinations of the Marquette region, made at different times in the summers of 1883, 1886, and 1887, have served to convince me thus far of the correctness of the views of most of the geologists who have examined the region with regard to the inferior position of the rocks of the greenstone-schist area to the remainder of the stratiform rocks. They have also served to impress me strongly with the probable correctness of the view which would make at least some granitic rocks subsequent in point of time to the greenstone schists themselves, since the latter are so intricately penetrated by granitic bosses and dikes in their more northern portions.

I have also seen enough to make me confident that the dike masses which cut the greenstone schists of this area are of wholly subsequent date to the schists, and indeed are equivalent in point of time to those intruded sheets and masses which lie within the overlying detrital iron-bearing series. On the other hand, I have seen some reason to suspect that nearly all previous geologists have been mistaken in considering the rocks of the greenstone-schist area as belonging within the same great geological period as that which holds the remainder of the stratiform rocks of the region. In other words, it thus far appears to me that there is good reason to believe that these greenstone schists along with the granites, gneisses, etc., form a portion of the basement upon which the overlying detrital iron-bearing series was once horizontally and unconformably spread. That they do not constitute the conformably underlying basement beds of that series is suggested by a glance at the map (Pl. I), from which it will be seen that they do not everywhere appear between the granite areas and the detrital rocks themselves, the granite at times coming in contact with them, and again with the higher stratiform horizons. But this anomalous arrangement

[1] Geological Report on the Upper Peninsular of Michigan, exhibiting the progress of the work from 1881 to 1884.

might possibly be explained by the eruptive nature of the granite, which, since eruptive, would come up indifferently at any horizon of the rocks intruded by it. However, that the granite is not newer than those stratified rocks which overlie the greenstone schists there appears very excellent proof. At a number of points where the detrital beds, which form the basement members of the iron-bearing series proper, come in contact with the granite, they contain its debris in a very notable fashion, while they are entirely devoid of granitic veins, such as occur where the greenstone schists come into contact with the granite. If, then, the granites are of one general age, it appears manifest that they are newer than the greenstone schists, but older than the overlying strata. Moreover, there are several points on the contact line between the detrital rocks of the iron-bearing series and the underlying greenstone schists, where a conglomerate is to be seen, in which are included not only numerous granitic fragments, but also large sized pieces of the greenstone schists themselves.

Since the occurrence of these basal conglomerates is a matter of so important a bearing on the geologic structure of this region, it is desirable that the points of their occurrence should be briefly indicated here. Beginning with the south side of the main, or southern area of the iron-bearing series, indicated on the accompanying sketch map, it may be noted in the first place that at several points along the contact line in Secs. 1, 2, 3, 4, and 5, T. 47 N., R. 25 W., the basal quartzite of the detrital series, which is in general made up almost completely of quartz fragments cemented by a siliceous matrix, takes on a peculiar character, containing at times a large quantity of pinkish orthoclase, along with a good deal of sericitic mica. This peculiar rock was regarded by Dr. Rominger as having been altered from the quartzite by its contact with the more recently erupted granite. A study of the thin sections, however, reveals the completely fragmental nature, not merely of the quartz, but of the feldspar pieces, while the sericitic ingredient appears to have arisen from an immediate alteration of the feldspar fragments. These feldspathic fragments, as also the quartz mingled with them, are of the kinds characteristic of granite, and, moreover, are entirely identical with those occurring in the granite with which this peculiar rock is in contact. Southwest of Goose Lake, however, in Secs. 21 and 22, T. 47, R. 26 W., there are much more obvious occurrences of granitic débris. In the lower detritals of the iron-bearing series near the southwest quarter of section 22 may be seen layers of fragmental quartz slate holding seams of granitic pebbles; while in the southeast quarter of the same section contacts are seen between the fragmental quartzite and masses of the granite, the quartzite at the contact being crowded with bowlders and fragmental material of all sizes derived from the granite. It is not evident whether the granitic masses here seen are brought to view by a fold of the strata, or are directly connected at surface with the main granitic mass lying to the southeast of them, the

exact outlines of the areas occupied by different rocks in this vicinity having never been traced. These occurrences were noted by Dr. Rominger,[1] who also describes similar ones as obtaining in the southwestern portion of the same township. It should also be said that, at numerous points along this line, the quartzite contains pebbly beds in which the pebbles are of a quartzite whose microscopic features prove to be those so well known as characteristic of the quartz of granite.

Turning now to the northern line of the same area we may note first the conglomerate to be seen on the side of the so-called State Road, running west from Marquette at a point near the west line of the SW. ¼ of the SE. ¼ sec. 29, T. 48 N., R. 25 W. This is exactly on the line between the greenstone-schist area and the area occupied by the detrital rocks, which just here are thinly banded slates, standing vertical or even overturned slightly so as to dip to the northward and to lie in general conformity to the cleavage of the greenstone schists immediately north. These slates, whose lithological character is one very commonly met with at the base of the iron-bearing series in many different portions of the Lake Superior region, are proved by the thin sections to be quite beyond question water-formed detritals and at the same time to present a most striking contrast with the hornblendic and chloritic greenstone schists lying immediately north of them. This contrast, however, though very distinct in the thin section, is by no means so pronounced in the hand-specimens which, though one sees that they are of two different natures, might nevertheless be readily taken to be all of the same origin. At the point indicated the fragmental slates become crowded with large and small fragments of granite, quartz, and green schist, the quartz pebbles usually being of rather small size, while those of granite, which are the most numerous, are well rounded and reach as much as two feet in diameter. The green schist pebbles, on the other hand, are not so plentiful, but are still abundant and of all sizes, from the smallest particles up to pieces a foot across. The larger schist pieces are somewhat rounded, but in the main they are all far less so than the fragments of granite and quartz. The thin sections cut from the matrix of the rock show that it is completely of a detrital nature. On the north side of Teal Lake, at both eastern and western extremities, are found other conglomerates, in one case holding only quartz pebbles, and in the other case pebbles not only of quartz, but of greenish schists as well.

Turning our attention now to the northern one of the two detrital areas indicated on the sketch-map herewith (Pl. I), I may note the occurrence at a number of points along its southern margin of conglomeratic layers of quartzite and sandstone, in which are contained pebbles of white quartz, which pebbles are at times identical in microscopic and macroscopic appearance with the quartz of certain seams in the greenish schists (as, for instance, on the west line of Sec. 20, T. 48 N., R.

[1] Geol. Survey, Michigan, vol. 4, 1881, pp. 62, 63.

27 W.), or with that of the granite (as, for instance, near the middle of the south half of Sec. 17, T. 48 N., R. 26 W.), against which different rocks the quartzites rest in different places. Near the middle of Sec. 21, T. 48 N., R. 27 W., the quartzite, resting here against certain agglomeratic green schists, contains not only fragments of quartz like that of numerous seams in the green schists, but also pieces of the green schists themselves, which in some cases are several inches in diameter.

But the most striking occurrences of basal conglomerates upon the edges of this area of detrital rocks are those to be met with in the northern and western portions of T. 49 N., R. 28 W. One of these places, to which my attention was first drawn by Mr. C. E. Wright, the state geologist of Michigan, is on the northwestern shore of Silver Lake, in the SE. ¼ of the NW. ¼ of Sec. 8. Rising abruptly all along the northern side of this lake is a bold ridge of granite with which are associated several kinds of schistose rocks, very prominent among which is a fine-grained green schist entirely analogous in general appearance to the greenstone schists which form the special subject of this paper. At the particular point to which attention is now directed, this granite protrudes in places into the lake in low, shelving ledges, facing which, and lying within the cracks of which, is a black cherty slate. Following the shore along to the southwestward from these exposures, the cherty slate is found more largely developed, occupying a large hollow in the surface of the granite, and becoming crowded with its fragments of all sizes, from a fine detritus up to pieces two feet in length. These fragments, though prevailingly subangular to angular in outline, generally present some evidence of water-wearing. Many of them are quite gneissoid in structure, while others are more granitic, two principal phases being thus presented. The thin sections made from the specimens selected on the ground as characterizing these two phases of pebbles, and also the granitic and gneissoid phases of the granite against which the conglomerate rests, show the entire indentity of the fragments and the massive granite. In addition to the granite fragments are rarer ones of white quartz, these occasionally being of some size, and others of a greenish schist entirely analogous to that green schist which occurs here in situ along with the granite. The matrix of this conglomerate is a dark gray to nearly black, carbonaceous, cherty slate, which in the thin section shows a predominating quantity of a cherty, chemically deposited silica, with which are mingled varying proportions of fragmental material, this fragmental material being composed of pieces of quartz and feldspar, and again, when the pieces become coarser, of a granite in which these same minerals are attached to each other. At times, as is so commonly the case among the cherty rocks of the iron-bearing series generally, throughout the Lake Superior region, there is a brecciated condition in this slaty matrix itself; that is to say, irregular, angular pieces of the carbonaceous cherty material are cemented together by a matrix of the same substance. Quite similar occurrences

are met with near the center of Sec. 19, of the same township, where black cherty slate and quartzite lie upon the east and south flanks of a bold hill of granite; both slate and quartzite, and particularly the latter, being crowded with fragments of the granite, which range from small pebbles up to pieces a foot or more in diameter, the smaller sized pebbles being usually quite well rounded, while the larger fragments are subangular to angular.

Such occurrences as these, when considered in connection with the manner in which the granite penetrates the greenish schists and is involved with them, seem to render necessary the belief that, while it is plainly younger than the green schists, it is nevertheless greatly older than the overlying detrital rocks; and more than this, that when the latter rocks were spread, the granites and greenstone schists together had already suffered disturbance and deep denudation. It does not appear possible to escape this conclusion by supposing that, since granite and greenstone schists are eruptives, they may have furnished fragments to almost contemporaneous sedimentary deposits; for, in the first place, both the greenstone schists and the gneissoid granite must have received their schistosity before yielding the fragments. Moreover, whatever may have been the depth at which the schistose rocks were first formed, the granitic masses which intruded them, according to all the later developments and doctrines of petrography, must have been crystalized in depth, and must therefore have had removed from over them great masses of materials before yielding fragments to wave action. In this connection attention should be drawn to the fact that there are evidently granitic rocks of two different ages in the great granitic areas of the Marquette region; because dikes of a fine grained, reddish granite are frequently met with cutting the other granite, which may be either gneissoid or not. These later granites, which appear to be of relatively small extent compared with the main mass, may perhaps have been even later in time of formation than the detrital rocks themselves. It seems probable that to these later granitic eruptions we should refer certain rare quartz-porphyry dikes, and such very rare granitic dikes as that which is seen near Metropolitan, in the Felch Mountain district, intersecting a ferruginous schist of the iron-bearing series itself.

On the whole, then, accepting Prof. Williams's conclusions as to the surface origin of most of the greenstone schists of the Marquette region, I should suppose that, after the accumulation of these rocks to the thickness of several thousand feet, they were intruded by granitic bosses. These bosses perhaps may have been merely softened portions of the underlying gneissic basement, which indeed may be represented in an unaltered condition in portions of the granitic areas themselves, for all that has yet been determined to the contrary. Subsequent mountain-making movements brought about the folding and alteration of these enormous sheets of eruptive material, now represented by

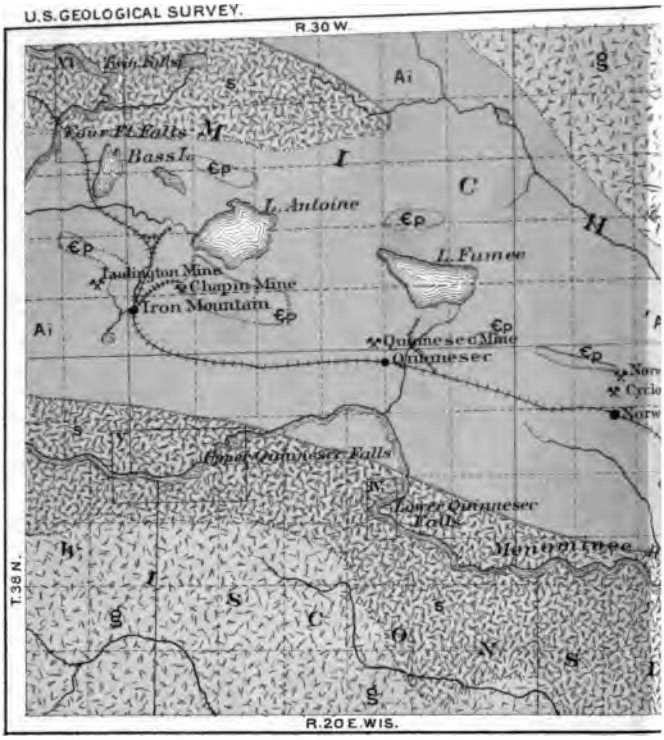
the greenstone schists. Following this was the great denudation which brought to light the previously buried granitic masses. This erosion was followed in turn by the accumulation in the usual horizontal position of the iron-bearing detrital series, whose folding and erosion were still later processes. And yet this folding and erosion all preceded the deposition of the horizontal Cambrian sandstones of the region.

The entire similarity which is shown by Prof. Williams to obtain between the great dikes of diabasic greenstone which traverse the greenstone schist area, and the sheets of eruptive greenstone which are included within the iron-bearing series, furnishes a further confirmation of these conclusions. For the latter greenstones are in large measure directly interstratified with the sedimentary layers of the iron-bearing series, following the bending of its layers; so that even if these greenstones are in the nature of intruded sheets, it seems necessary to believe that their intrusion took place before the folding of the iron-bearing series. Now, the corresponding dikes in the greenstone-schist area were evidently intruded subsequent to the production of the schistosity of the intruded rocks. If, then, these are facts, the time when the iron-bearing series was folded was very much subsequent to that time at which the greenstone schists received their schistosity. It has been mentioned that the schistose structure of these greenstones at times corresponds with the bedding structure of the iron-bearing series. But quite frequently there is no such correspondence, the beds of the latter series being noticeably at relatively lower angles when compared with the vertical schistose structures of the greenstone schists themselves.

Such correspondence in some places and lack of correspondence in others are easily enough explicable upon the views that I have advanced. However, there is good reason to think that at the time of the folding of the iron-bearing series, the greenstone schists received a second squeezing, which developed further alterations and further schistosity. The later dikes just alluded to as penetrating the green schists are at times rendered somewhat schistose, though far less markedly so than are the rocks which they intrude. The same is true with the greenstones that are intercalated in the iron-bearing series, where somewhat schistose phases are found. The structure of these last-named schistose phases, as also the occasional slaty cleavage seen in the detrital layers of the iron-bearing series, where it is very strongly folded, correspond in general direction, as would be expected, with the schistose structure of the greenstone-schist areas.

The geology of that portion of the Menominee region which has been especially under study in the present connection, is indicated by the outline map, Plate II. Here, again, we find a series of detrital iron-bearing rocks, lying between great areas of granite and gneiss. The iron-bearing rocks are generally quite closely like those of the Mar-

U.S. GEOLOGICAL SURVEY.



ARCHEAN.

Granite and Gneiss. Greenstone Schists. (De

OUTLINE GEOLOGICAL MAP OF

Compiled by R.D. Irving from maps by T. B. Brooks, C.E.

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quette region, the only important differences being the very great rarity of greenstone intrusions, and the very much more closely crumpled condition which the rocks here present. In the same region are two belts of greenstone schists closely analogous in general appearance with those of the Marquette region. The southern one of these borders for a long distance the southern granite area, separating the granite from the detrital rocks further north. The inclination of the schistosity of the greenstone schists is almost vertical, there being generally a slight southern departure from verticality. Very high southern dips, often approaching verticality, also prevail among the layers of the detrital succession itself, although here frequently occur reverse dips to the northward, often at a flatter angle.

The first geologists who appear to have noted the Menominee rocks are Foster and Whitney and Charles Whittlesey, as quoted in Foster and Whitney's work.[1] By these writers all of the Menominee stratiform rocks, so far as they were encountered in the rapid trips by canoes, which were at that time the only means of traversing the country, were classed together under the general name of Azoic slates. However, the exposures of greenstone schists, which are met with at Twin Falls, Upper (Big) and Lower (Little) Quinnesec Falls and Sturgeon Falls, appear to be directly referred to as intercalations of "Azoic slates and traps;" so that, while no opinion was expressed as to their stratigraphic relations to the other rocks of the region—beyond what is indicated in general statements as to the greater recency of all the granitic masses ot the region as compared with the schistose and slaty rocks—it appears plain that these geologists looked upon the rocks now included under the term of greenstone schists as partly eruptive and partly sedimentary.

The same conclusion as to the origin of these rocks appears to have been reached by Credner, who published an account of this region in 1869,[2] after having been some time on the ground as an assistant to Prof. R. Pumpelly in a private economic examination of the lands of the Lake Superior Ship Canal Company. On account of the slight departure from verticality towards the south; on account of the schistose structure of the rocks exposed at the several falls of the Menominee, which rocks he describes under the general term of "Dioritic Series' and "Talcky Clay Slate," and because of the prevalence of similar southern dips among the detrital iron-bearing rocks farther north, Credner considers the former rocks as constituting the highest portion of the entire succession of the region. That there existed to the south of these rocks another mass of granite does not appear to have been realized by Credner.

T. B. Brooks, who followed Credner in the Menominee region and

[1] Geological Survey of the Lake Superior Land District, vol. 2, pp. 24–31. See also general section of the Lake Superior region in atlas to the same volume.

[2] Die vorsilurischen Gebilde der oberen Halbinsel von Michigan in Nord-Amerika. Zeitschr. Deutsch. geol. Gesell., Berlin, 1869, vol. 21, pp. 516–554.

who published a brief account in the reports of the Geological Survey of Michigan[1], appears to have agreed with that geologist with regard to the relatively high position in the series of the greenstone schists of the Menominee River. Subsequently the same geologist, assisted by C. E. Wright, was engaged in a more minute examination of this region on the part of the Wisconsin State Geological Survey, publishing a somewhat elaborate report in 1880.[2] In this report very many more facts are given than were ever known before, all exposures seen being very accurately and carefully indicated upon the accompanying maps. This detailed work, however, does not appear to have altered Brooks's opinion as to the relatively high position in the Menominee series of the greenstone schists now especially under consideration, although it appears that he would now correlate them with still higher layers of the Marquette series rather than with those to which he had previously referred them. As to the origin of the greenstone schists, Brooks would seem to have regarded them at first as all sedimentary; at all events when the Michigan report referred to was written.[3] Later, however, he appears to have been disposed to separate from the rest certain diabases as eruptive, thus coming nearly to the same conclusion as that reached by Credner.[4] To convey Brooks's conception of the structure of this region more clearly, there are given here two sections, constructed from general sections given by him upon Plates 27 and 29 of the atlas to the Geology of Wisconsin. The granitic

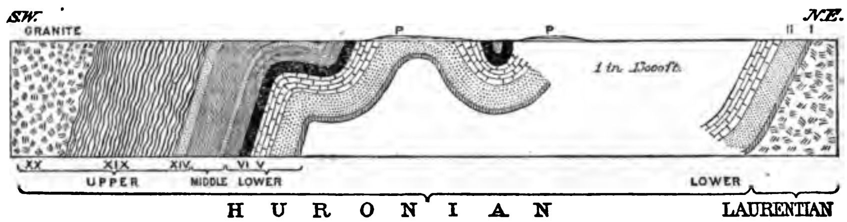

FIG. 1. Hypothetical section of the Menominee region in the vicinity of Quinnesec, according to Brooks; I, Sericitic slates; II, quartzite; V, limestone; VI, the great iron horizon; XIV, quartzite; XV to XIX, greenstone schists, etc.; XX, Huronian granite; P, Potsdam sandstone. Scale 13,000 feet to the inch.

and gneissic rocks to the north Brooks regarded as having formed part of the ancient Laurentian basement upon which all of the slates and schists were subsequently piled. From this northern granite to the granite on the south side of the Menominee he looked upon the entire succession as an ascending one, though admitting certain bowings of the strata. The southern granite, as to whose sedimentary or eruptive origin he appears to have been doubtful, he places as the summit member of the Huronian series. The entire succession he divides into three portions, beginning below or to the north, as follows: Lower Huronian,

[1] Geol. Michigan, vol. 1, 1873, pp. 157-182. See also atlas to the same, Pl. 4.
[2] Geol. Wisconsin, vol. 3, 1880, pp. 430-663; also atlas, Pls. 28-30.
[3] Geol. Michigan, vol. 1, 1873.
[4] Geol. Wisconsin, vol. 3, 1880, p. 521.

5,200 feet; Middle Huronian, 3,100 feet; Upper Huronian, 10,700 feet; making in all a maximum thickness of 19,000 feet beneath the upper or southern granite. The surface distribution of the uppermost of these three divisions corresponds almost exactly with the areas of greenstone schists indicated upon the outline map herewith (Pl. II). The more north-

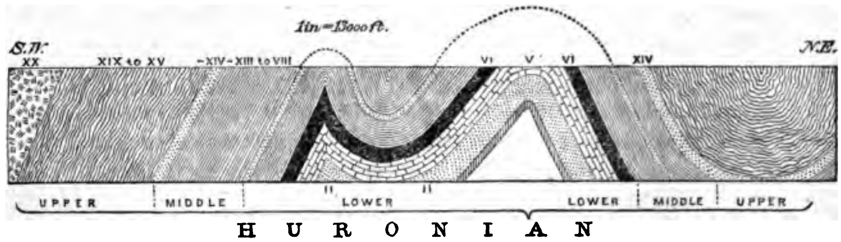

FIG. 2. Hypothetical section of the Menominee region in the vicinity of Twin Falls, according to Brooks. Scale 13,000 feet to the inch. Letters and shadings have the same significations as in Fig. 1.

ern area of greenstone schists, namely, that which is sectioned by the Menominee river at Twin Falls, is made on Brooks's structural sketches to be brought to view by a synclinal depression of the strata. For this view of the structure of the region there never was any other support than the very slight departure from verticality towards the south of the schistose structure of the southern greenstone schists and a prevailing similar inclination in the detrital iron bearing series proper. No contacts of the different kinds of rocks were observed to support Brooks's hypotheses as to the relatively high position of the greenstone schists and southern granite, between which and the other stratiform rocks there is indeed usually a wide belt of country without exposures. On the other hand, the extraordinary similarity of these greenstone schists to those which Brooks regarded as underlying the entire Marquette series appears to have been disregarded, as also was the complete similarity between the northern and southern granites, and again between the contact of the southern granite with the greenstone schists next to it, and the corresponding contact in the Marquette region.

Rominger, who followed Brooks in the Menominee region in 1880 and published an account of his observations in 1881, appears[1] to have realized very vividly the difficulties met with in accepting Brooks's structural hypothesis. He represents all of the greenstone schists of the region as belonging at the base of the entire stratiform series, and as equivalent in position and nature with the similar rocks of the Marquette region. The northern and southern granites Rominger looks upon as the same, and as intrusives of a date later than the accumulation of the entire stratiform succession. As to origin, he evidently looked upon the greenstone schists as altered sedimentaries, assigning the relatively great alteration, which on this view they must be assumed to have undergone, to the action of the later granitic bosses; in which

[1] Geol. Survey Michigan, vol. 4, 1881, pp. 157-241.

view he fails quite to explain, as he does in the case of the Marquette region, how the southern granite of the Menominee area should have produced so great alterations, while that on the north comes in contact with wholly unaltered detrital rocks, to which moreover, as Brooks had previously shown, it furnishes an abundance of detrital material. Unfortunately, though describing carefully very many exposures not recorded on Brooks's map, Rominger gives no sections indicative of his views as to structure. Just what his ideas were in this respect it is not easy to make out from his descriptions, but it appears evident that with him the greenstone schists lie at the base of the succession; that they are next succeeded in order by those slates which lie about Lake Hanbury; that these are succeeded by the great ore horizon, and this by the great limestone bed of the region with a thickness of a thousand feet and more. Thus he reverses entirely the succession as given by Brooks, and as it appears in nature so far as the limestone and ore belts are concerned. What stratigraphical position Rominger would give to those great masses of quartzite which lie adjacent to the northern granite in Menominee belt I have not been able to understand distinctly from his descriptions. The Twin Falls greenstone schists he would place along with the Quinnesec series at the base of the entire succession, bringing them to the surface by an anticlinal instead of a synclinal fold, such as is resorted to by Brooks. The following paragraphs are quoted from Rominger,[1] as indicative of his views upon these points:

A superposition of the diorite formation on the Lake Hanbury rock series, which adjoins in the whole length of the Menominee valley from the upper Quinnesec Falls to the Sturgeon Falls, asserted by Major Brooks, is not observable; the nearly vertical strata of both formations are even never seen in contact. There is always quite a large covered interval between them. The nearest exposures of the two groups are observable in Sec. 26, T. 39, R. 29, where, in the center of the section, a hill is formed of the vertical ledges of ferrugino-siliceous flagstones and slaty beds representing the Lake Hanbury series, and about two or three hundred steps from these exposures we find on the south side of the road to Menominee small hillocks of diorite. * * *

My reasons for holding the dioritic rocks south of the iron formation as older than the latter are based on the lithological similarity of this formation with the dioritic group of the Marquette district and on the degree of metamorphism exhibited by the two groups, the dioritic and the iron-bearing. In the great succession of strata commencing with the Hanbury slate group and upward we rarely find a bed so much altered that its sedimentary structure is altogether obsolesced, and the majority of the strata shows it very plain, while in the dioritic rocks, considered to be the younger, a stratified structure is also recognizable, but not one of these thousands of feet of ledges exhibits its original sedimentary lamination with any degree of distinctness like the others; they have evidently been transformed under cooperation of heat and partially brought into a plastic condition, which is shown by the extreme corrugation and mode of intermixture of those rock masses, of which effects the other rock groups do not exhibit near as high a degree. It would be very strange, then, if the lowest beds nearest to the focus of the central heat should have been so much less affected by these altering influences than those pretended to be the higher upper strata of the rock crust. One might object: If the diorites are the older beds, why don't we find them just as well developed on the north side of the upheaved beds between the quartzite and the granite? The sandy and conglomeratic nature of

[1] Geol. Survey Michigan, vol. 4, 1881, pp. 208–210.

many of the strata of the quartzite and iron formation proves them to be shore deposits, while the dioritic group consists only of the finer material of deep sea deposits, which explains the point in question. Moreover, the dioritic rocks are not altogether missing on the north side of the ore-formation, as we can see by the occurrence of the 6-mile-long chain of diorite extending eastward from the Twin Falls. A similar discrepancy between the rocks underlying the ore-formation on the two opposite sides of its exposure is seen in the Negaunee district. On the south margin, at the Cascade and Palmer mines, it rests directly on the granite, while on the northern exposures the diorite underlies it in great thickness.

The equal dip of the strata to the south in these adjoining formations is not necessarily a proof of the younger age of the most southern beds. The whole succession is so near to a vertical position that in many instances it has to be left uncertain which way they dip, but suppose their dip is conformably to the south; the upheaval of the diorites by the eruption of the still more southern granite masses pushing the whole incumbent rock-series north until all tipped over is the hypothesis by which I explain the order in the succession of beds as an inverted one, the seemingly lowest beds being actually the youngest.

In my own studies in the Menominee region, made in the summers of 1883 and 1885, I became early impressed with the close similarity between the greenstone schists of the Menominee River and those which underlie the iron-bearing series of Marquette; with the entire similarity between the rest of the stratiform rocks of the region and those of the Marquette district; with the essential identity in character of the granite areas lying respectively on the northern and southern sides of the Menominee River; with the granitic intrusions met with in the greenstone schists bordering the southern granite, and with the striking contrast between the nature of this contact and that of the northern granite with the detrital rocks which border it to the south. In the latter case the granite, instead of sending intrusions into the rocks which rest against it, has furnished fragments to them, as may be most beautifully seen at the Falls of Sturgeon, Sturgeon River, on the eastern side of Sec. 8, T. 39, R. 28 W., Michigan.[1] These considerations naturally

[1] For previous descriptions of the striking occurrences at the Falls of Sturgeon, Sturgeon River, see Credner in "Die vorsilurischen Gebilde der oberen Halbinsel von Michigan," Zeitschrift der Deutschen geologischen Gesellschaft, vol. 21, 1869, p. 521, et seq.; also T. B. Brooks, in Geol. Wisconsin vol. 3, 1880, pp. 467, 468, and Atlas, Pl. 38; also, see Rominger, Geol. Michigan, vol. 4, p. 192. The granitic fragments at this place occur in a fine-grained slaty rock, in which there is a great deal of sericitic material, which at times gives the slate somewhat the look of a crystalline schist. This fact, along with the slight inclination from the vertical towards the north, and therefore towards the granite, which is so largely exposed farther up the stream, led Credner to include these conglomeratic layers, along with the granite, as Laurentian, the great quartzite mass farther south being taken by him as the basement member of the Huronian. Brooks, however, objects to this conclusion, considering that the conglomerates to be seen at this place are genuinely basal conglomerates, and that they form the lowest portion of the Huronian region. To support this view, Brooks draws attention to the frequent arenaceous nature of the conglomeratic slates; their ripple-marked surfaces; their generally little altered appearance; their parallelism of strike with the admitted Huronian beds farther south, and the lack of parallelism between this strike and such structures as is to be seen in the granitic and gneissic rocks on the north. Rominger's description corresponds with that of Brooks, except that he seems to describe a granitic mass or sheet as occurring interleaved with the conglomerates themselves, a statement for which, in my examinations, I could find no support whatever. Rominger, however, to whom the greater recency of all the granite as compared with all the stratiform rocks was an accepted conclusion, explains the occurrences as he saw them by the singular supposition that "we have here evidently a series of sedimentary beds, deposited on a granitic substratum, which, during the upheaval, became wedged in between the plastic granite mass, tilting and overlapping them locally so as to appear as the lower beds," thus making the same granite yield fragments to the sedimentaries, and subsequently intrude them. It should be said that the examinations of the several geologists were

led me to the conclusion that the whole structure in this district is similar to that already described as obtaining in the Marquette region, namely, that the granitic masses had intruded themselves in the shape of great bosses into rocks now represented by the greenstone schists, after which followed a protracted period of disturbance and denudation before the deposition of the overlying detrital and iron-bearing rocks of the region. Taking Major Brooks's detailed map of the Menominee district, published in the atlas of the Wisconsin survey, I platted upon it all of the exposures described by Rominger and not mapped by Brooks, which exposures amount in all to a large number. Examining, then, the more important of the exposures of the region, I encountered still others, which were also platted upon the same map. Two sections were then constructed across the district from southwest to northeast, upon which were platted all of these exposures, with their dips; and it should be said that very many new facts in this direction have been developed of late years by mining.

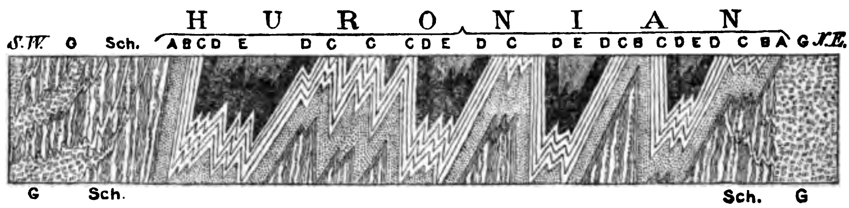

FIG. 3. Hypothetical section of the Menominee region in the vicinity of Quinnesec Valley, according to R. D. Irving. A, basal sericitic quartz slates; B, quartzite; C, limestone; D. iron horizon; E, slates and quartzites; G, granite and Sch., schists of the Laurentian. Scale, 13,000 feet to the inch.

It has thus become evident that a structure such as is indicated in the accompanying Fig. 3 would not only coincide with the recorded facts as well as the sections of Brooks above given, but very much better than those.

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made without the study of thin sections of the slaty rocks here exposed. When examined microscopically, these rocks show their completely fragmental nature, all the alteration that they have undergone having been in the nature of a metasomatic development of mica flakes. Both hand specimens and thin sections of these slates, moreover, show a most striking similarity between them and the slaty rocks which frequently lie at the base of the Penokee series of northern Wisconsin and Michigan, where they are often in contact with granitic rocks, of which they hold fragments. Similar slates are met with in a number of places at the base of the iron-bearing series of the Marquette region. As seen at the Sturgeon Falls, these slates are at times fine grained and thinly laminated, arenaceous and sericitic, and again more closely grained and of a vitreous quartzitic appearance, in which cases the predominating quartz fragments have been cemented together by secondary enlargement. Their entire ack of anything like metamorphism is perfectly plain, even without the examination of the thin section, to any one who has studied many sections of such rocks from the Lake Superior country. The pebbles in these slates are arranged in bands, with intervening less pebbly or non-pebbly portions, which portions are the ones which show particularly the ripple-marked surfaces. The pebbles are in the main of a pinkish granite and gneiss, wholly identical with the mass of granite and gneiss against which they lie, but include also a smaller number of pieces of white quartz and of a fine-grained greenstone or greenstone schist. Entirely similar quartz occurs in seams in the granite close by, as do also masses of greenstone and greenstone schist. Not only these pebbles, but the whole make-up of the finer portion of the rock, make it entirely evident to me that we have here to do with a detritus derived by water action from the granitic and gneissic area immediately to the north. The slight inclination away from the vertical towards the granite which these conglomeratic slates sometimes show is, of course, no argument against their having been deposited upon that granite as a substratum.

THE GREENSTONE SCHIST AREAS OF THE MENOMINEE AND MARQUETTE DISTRICTS, MICHIGAN.

By GEORGE HUNTINGTON WILLIAMS.

INTRODUCTION.

This memoir is intended as a contribution to the subject of dynamic or regional metamorphism. It contains the results of a careful study, both in the field and in the laboratory, of an extensive series of eruptive rocks, for the most part of basic character. Although the original character of these rocks is still evident, they are to a large extent cleavable, and the production of this secondary feature has been accompanied by more or less extensive chemical and structural alterations.

It is the aim of this paper to trace each of the rock types represented within the areas studied from its least altered to its most altered form, and to discuss what may have been the agencies which produced the changes noticed.

The rocks selected as likely to throw additional light upon the metamorphism of eruptive masses are so-called "greenstones" and "greenstone schists," which, in association with certain more acid types, cover extensive districts on the south shore of Lake Superior, where they lie immediately beneath the iron-bearing strata Two distinct and sharply defined areas of these rocks were chosen as typical of the whole formation. Particulars regarding their geographical positions and their geological relationships have already been given by Professor Irving in his preliminary note. In the first area, situated on the Menominee River, the eruptive character of the greenstones and greenstone schists is plainly evident; within the second area, near the city of Marquette, the original character of the rocks is much less apparent.

The investigations, the results of which are embodied in this memoir, were first suggested to me in the spring of 1885 by the late Prof. R. D. Irving, while he was in charge of the Lake Superior division of the U. S. Geological Survey. Their aim was to discover, if possible, the origin of the greenstone schists of the Lake Superior region, and at the same time to afford a contribution to our knowledge of the metamorphism of basic eruptive rocks in general. In the latter sense they form a continuation of the writer's earlier studies of the less altered gabbros occurring near Baltimore, Maryland.[1]

[1] Bull. U. S. Geol. Survey, No. 28, 1886.

Three weeks of the field season of 1885 were spent in the Menominee Valley, and four weeks of 1886 in the neighborhood of Marquette. During this time, with the assistance of Prof. W. S. Bayley, the rocks were examined in the field, and ample material was collected for their laboratory study, which was carried on at the Johns Hopkins University, Baltimore, Maryland, during the winters of 1885–'86 and 1886–'87, at such times as could be spared from regular university duties. The entire investigation has been conducted under the auspices of Professor Irving, for whose uniform kindness and constant readiness to supply every facility for the work I gladly take this opportunity of expressing my sense of deep obligation. My thanks are also due to Maj. T. B. Brooks and to Prof. Raphael Pumpelley for the loan of microscopic sections of the Marquette and Menominee rocks, prepared during the course of the Wisconsin State Geological Survey; and to Mr. Andrew C. Lawson, Ph. D., lately of the Canadian Geological Survey, for the opportunity to make a comparative study of closely allied rocks from the Lake of the Woods and the Rainy Lake regions.

I feel that no especial apology is needed for the constant use throughout this paper of the term "greenstone." An opinion prevails that this word is antiquated and not consistent with the scientific accuracy now obtainable. The very indefiniteness of this designation, however, constitutes its chief value. It is essentially a field term, such as it is not only desirable but absolutely necessary to employ. It is often impossible to state with certainty in the field whether a given basic massive rock is a gabbro, a diabase, or a diorite; indeed, where such masses have undergone extensive metamorphism, as in the regions here studied, even the most careful microscopical and chemical investigation may prove inadequate to disclose what was the original form. Wherever accurate diagnosis was possible, correspondingly definite terms have always been employed; but for use in the field or where the processes of alteration have obscured the original character of the rock beyond recognition, an intentionally indefinite designation is necessary. For such a purpose it is believed that no term is better fitted than the ancient and much abused "greenstone."

For convenient reference the specimen numbers belonging to the collections of the Lake Superior division of the U. S. Geological Survey are here appended.

1. *Menominee Valley*	11000–11196
Sturgeon Falls	11153–11174
Little Quinnesec Falls	11000–11048; 11098–11103
Big Quinnesec Falls	11049–11085
Horse Race	11086–11096; 11182–11196
Four Foot Falls	11142–11152; 11175–11181
Twin Falls	11120–11141
2. *Marquette region*	11610–11864
Marquette area	11610–11734
Negaunee area	11735–11812
Northern area	11813–11864
3. *Agglomerates of Deer Lake*	12023–12058

The material embodied in the present paper will be arranged in three separate divisions.

1. In chapter one the importance of the service which the microscope is capable of rendering toward the solution of the questions of archæan geology will be indicated and a summary presented of the chief results already obtained by various workers in this field.

2. In chapters two, three, four, and five the observations collected during an extended study of the rocks of the two areas selected will be given in detail.

3. In chapter six a connected discussion of these results will be attempted, and a comparison of them with those reached by other observers, as enumerated in chapter one, will be made.

CHAPTER I.

PRESENT STATE OF OUR KNOWLEDGE REGARDING THE METAMORPHISM OF ERUPTIVE ROCKS.[1]

VALUE OF THE MICROSCOPE IN THE STUDY OF METAMORPHISM.

In comparison with the results which have been obtained during nearly a century of patient research among sedimentary deposits, the progress thus far made in the domain of archean geology appears small. Theories of the origin of the so-called crystalline schists are almost as numerous as the investigators who have examined them, and yet the more extensive and critical the studies of these rocks become the more obscure and anomalous do they appear. So varied are the facts which Nature presents to the observer in the oldest rocks of the planet that the conviction is soon reached that no single hypothesis or explanation can account for them. It is therefore from no lack of interest attaching to the study of pre-fossiliferous rocks that they have heretofore yielded so little fruit, but rather from the insurmountable difficulties which have stood in the way of their satisfactory investigation. That the study of fossils has made up so large a part of what has been known as geology is the result rather of necessity than of choice. The lack of exact and delicate methods of lithological research has confined the attention of investigators to those formations where lithological characters are of little value on account of the presence of other and more certain guides. The basement underlying all of the fossiliferous rocks has, therefore, remained well-nigh a terra incognita, because there seemed to be no available means of exploring it.

The recent multiplication of refined methods for the investigation of crystalline rocks, however, has opened an almost new field of geological inquiry. The difficult and obscure problems here presented may now be attacked by truly scientific methods. The prophecies which Hermann Vogelsang made in 1867[2] for the new departure in geology have been more than realized within the last twenty years. The almost new science of petrography may be said to have proved itself capable of rendering, in the study of the crystalline rocks, a service equal to that which paleontology has already given in the deciphering and correlating of the fossiliferous strata.

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[1] This chapter was written as it now stands, excepting an occasional foot note, in 1887.

[2] Die Philosophie der Geologie, Pt. 3, Moderne Geologie oder mikroskopische Gesteinsstudien.

Petrography, in its rapid development since the introduction of the microscope, has already passed through two distinct periods and is now entering upon a third and most important stage. At first methods had to be perfected for identifying the various constituents of crystalline rocks. During this stage the science was purely mineralogical, although its methods were necessarily somewhat different, both in their nature and in their application, from those of ordinary mineralogy. The attainment of this end required the study of a vast amount of material wholly without reference to its geological significance.[1]

The second period in the development of petrography was occupied with the investigation of practically unaltered rock-types, i. e., of rocks in which the minerals and structure produced by their original solidification are still readily discernible. It has been found from such studies that the relationship of the component minerals to one another, or rock-structure, expresses, to a large degree, the circumstances under which the original solidification took place, and hence the importance of the second stage in the development of modern petrography.

The most important problems presented by an unaltered massive or igneous rock relate to (1) its chemical composition and (2) to the conditions under which it was formed. The composition expresses itself, in a general way, in the nature of the component minerals, while physical conditions attendant upon the formation of the rock may be traced in its structure. Each of these has therefore been, in turn, the particular object aimed at during the first two periods of petrographical research.

But if petrography were able to solve satisfactorily all the problems presented by the unaltered massive rocks, it would even then be prepared only to commence its most difficult and most important mission. Rocks are in reality far from being the dead, inert, stationary masses which they appear to the ordinary observer. The fascinating study of chemical geology, especially when aided by the microscope, shows them to be in a state of almost constant change. It is true that some of the oldest rocks seem to have suffered hardly any alteration since they were first formed, but most of them are ever active laboratories where old products are being pulled to pieces and new ones built up. The tracing out cf such changes is an important aim of petrography in its present stage.

The student at the microscope wonders at the minute bubbles which he so often finds inclosed in the little cavities in quartz. So delicately are they poised that they are sensitive to all the slight oscillations of temperature that constantly pass through the microscopic section, and the little prisoners keep up a never-ending movement, as though beat-

[1]The writer has given an account of the development of these methods in a small pamphlet, entitled "Modern Petrography," published as No. 1 of the Monographs of Education, by Heath & Co., of Boston.

ing against every side of their narrow cell in the vain search for an exit. Scarcely less delicate seems to be the equipoise between the various chemical compounds in the earth's crust and the surrounding physical conditions under which they exist. Like the constant changes of temperature which pass through the slide are the changes in physical conditions to which a rock-mass is subjected. With these comes a state of more or less unstable equilibrium to the chemical compounds, and, like the vibrations of the bubble, molecular movements and rearrangements result.

There are two distinct kinds of alteration which take place in a solid rock-mass, dependent, of course, on the nature of the changed physical conditions. These are:

(1) *Metamorphism;* or the passage, under circumstances of high temperature or pressure, or both, of less crystalline into more crystalline compounds; or the change of minerals into others, not less crystalline or insoluble than themselves.

(2) *Decomposition or weathering;* the passage, under ordinary atmospheric conditions, of crystalline rock constituents into compounds less crystalline and more soluble than themselves. This is accomplished generally by hydration or carbonatization.

Both of these processes are frequently seen to have gone on in succession in the same rock-mass, the latter more or less completely effacing the effects of the former. While distinct, both processes agree in being atomic and molecular rearrangements in a solid mass, necessitated by some change in external conditions. The differences in these conditions, however, produce widely different results; and all of these again are essentially different from those produced by the solidification of a liquid magma.

The student of the crystalline rocks can distinguish in a general way four classes of constituent minerals, and this is true in spite of the fact that the same species may be represented in two or more of these classes.

(1) Original minerals of the acid rocks, formed by solidification of a magma in a state of aqueo-igneous fusion or by the aid of mineralizers; e. g., quartz, orthoclase, mica, zircon, etc.

(2) Original minerals of the basic rocks, formed from a state of dry fusion; e. g., plagioclase, augite, olivine, etc.

(3) Metamorphic minerals, formed, as above explained, from original minerals; e. g., hornblende, albite, biotite, zoisite, garnet, staurolite, andalusite, etc.

(4) Decomposition minerals; e. g., chlorite, quartz, carbonates, the hydroxides, etc.

Such a division, though necessarily not a sharp one, is still not unwarranted and shows how it is possible, with the aid of the microscope, not merely to study the composition of a rock in its component minerals, or the conditions under which it was first formed in its

structure, but also to trace out life histories. We may discover not only the conditions under which a rock-mass solidified, but we may learn as well something of all the conditions to which it has subsequently been subjected.

Metamorphism, or the recrystallization of rocks, whether massive or stratified, igneous or sedimentary, is as varied in its results as the materials acted upon and the agencies which produce it. How true this is may be seen where the cause of the change is local and well understood, as in the numerous instances of contact-metamorphism which have been studied in detail during the last fifteen years. Here the alteration produced by the same eruptive mass is different in a shale from that in a sandstone, and in each the alteration is quite distinct from that produced in a limestone. If intrusive rocks fall within the range of influence, the effects produced in them are again different; while still wider variations are noticeable if the character of the active or metamorphosing rock be changed. This may be seen in the contrast between the effect produced by a mass of granite and a mass of diabase upon the same surrounding rock. Still other differences are traceable to the probable action of vapors, as in the case of a local development of tourmaline or topaz within the limits of a granite contact zone.

How much greater then might we expect the differences to be which all the complicated and imperfectly understood conditions of regional metamorphism produce. Many rocks occupying large areas exhibit a character very similar to that of rocks which have been produced by contact-metamorphism, without there being any cause to which the alteration can be so directly attributed. In some schists, like those of the Ardennes Mountains[1] and those of Bergen in Norway,[2] and in many limestones, metamorphic minerals have been extensively developed without the total obliteration of organic remains. In the case of other rocks, of essentially the same character though perhaps more crystalline, the internal evidence or the stratigraphical relations are enough to prove that they are metamorphosed sediments.

Many of the so-called crystalline schists present features of both composition and structure which are strikingly similar to those of rocks of undoubted metamorphic origin, but nevertheless we have at present but few data for constructing a satisfactory explanation of the origin of these enigmatical formations. Theorizing in regard to them has done its best, and has succeeded in introducing only confusion and disagreement. As before remarked, the variety here is far too great to be accounted for by a single hypothesis, however broad. Many agencies have been at work, whose exact nature and importance only the most laborious and patient investigation can show. In working in Archean

[1] A. Renard: Les roches grenatifères et amphiboliques de la région de Bastogne. Bull. Mus. Roy. Hist. Nat. Belgique, 1882, vol. i, pp. 1–54.

[2] H. H. Reusch: Silurfossiler og pressede Konglomerater i Bergensskifrene, 1882. Germ. transl. by by R. Baldauf.

geology the only safe method is to free the mind completely from all traditions and theories—to start with the idea that almost nothing is known with certainty and that everything is to be discovered. The facts must be most critically observed and considered, without too great a tendency to use them at once for the deduction of general principles. Only such conclusions as can not be doubted by any one who will take the pains to examine the facts are of real value to the advance of archean geology; and every careful student in the field must realize how slow and difficult such an advance must be. Detailed analyses of the workings of some well recognized agency, made where the action has been as little as possible disguised and complicated by the action of other agencies, must yield valuable assistance in the penetration of the mysteries which now everywhere surround the prefossiliferous formations of the earth's crust. Such work has been done in Europe and has been begun in America. The little that has already been accomplished in this manner is full of promise for the future. The most striking example of work of this kind is perhaps that of Lossen in the Hartz Mountains, and it is with the sincerest appreciation of his method and results that the present studies have been prosecuted.

If it be granted, as it must be, by every impartial observer that such a thing as regional metamorphism does exist—that certain rocks, when they are subjected to enormous strains, and are upheaved, crushed, and crumpled do become more crystalline or have their crystallization altered—then we have a well recognized agency whose particular results are worthy of patient and detailed study. What part regional metamorphism has had in the production of the archean rocks as a whole, future years must show. This question lies wholly without my present purpose; and yet it is hoped that an extended investigation of a particular phase of it may aid in the final solution of the problem.

The investigation was undertaken with a firm conviction of the peculiar advantages offered by eruptive rocks for the accurate tracing of progressive metamorphism, an advantage which Prof. A. K. Lossen seems to have been the first to emphasize, if we may judge from the following extract from one of his papers. He says:[1]

> I attribute the extreme value of such metamorphosed eruptive rocks for the general theory of metamorphism to the fact that they are certainly known to have been derived from a solid rock of definite mineral aggregation, average chemical composition and structure. In the primary minerals and structures of the igneous rocks we possess a well known quantity, upon which we can base our conclusions—a definite scale according to which the nature and amount of those secondary minerals and structures characterizing the metamorphic rocks can be measured. Frequently the certain, incontestable fact of pseudomorphism proves the secondary alteration of these rocks in a much more general way than even the very exceptionally preserved fossil remains are able to prove the origin of metamorphosed sediments.

[1] Den hohen Werth dieser metamorphischen Eruptivgesteine für die Lehre vom Metamorphismus fand ich darin, dass ein von Haus aus *festes Gestein von ganz bestimmter Mineralaggregation, chemischer Durchschnittszusammensetzung und Structur*, zuverlässig als ihr Muttergestein angegeben werden kann. In den primären Mineralien und primären Structuren der Erstarrungsgesteine besitzen wir eine

There is no student of mineralogy who has not been struck with the great similarity which exists in the composition of so many of the rock-forming silicates.

We have after all a very small number of bases in these silicates and they are often combined in almost the same proportion in minerals which show the greatest disparity of crystal form, physical properties, and mode of occurrence. It seems to be oftentimes more a matter of external condition rather than of chemical composition, which determines what particular mineral is formed; and the equipoise between the existence of a certain silicate and the external conditions is often so delicate that a mere change in the latter is alone sufficient to destroy the mineral as such and to cause it to change to some other modification or compound. The recent discoveries of the alterations which dimorphous bodies, like leucite or tridymite undergo, show how this may be accomplished without chemical change. The breaking up of a mineral into an aggregate of two or more is not less common; as for example, the passage of plagioclase into zoisite and albite (saussurite), or of spodumene into albite and eucryptite (the β-spodumene of Brush and Dana.)[1] This subject has lately been elaborated by Prof. J. W. Judd in his presidential address before the Geological Society of London, and in many others of his recent papers.[2]

Rocks whose component minerals are so delicately balanced to accord with the particular set of conditions under which they were formed, must be peculiarly subject to alteration when these conditions are changed; and for this reason the writer has before insisted that eruptive rocks must be even more liable to metamorphism than the sediments which contain them.[3]

The advantage, then, of eruptive rocks, especially of basic eruptive rocks, for the study of metamorphic processes is, as Lossen has remarked with so much force, because we have in them a set of minerals and structures which can with certainty be referred to eruptive conditions, i. e., conditions of fusion. These, at least for the basic rocks, may be easily reproduced in the laboratory, as has been so successfully done by

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wohlbekannte Grösse, die wir unserem Urtheil zu Grunde legen können, einen festen Maassstab, an welchem Art und Grad jener secundären Mineralien und secundären Structuren gemessen werden können welche die Natur des metamorphischen Gesteins mehr oder weniger ausmachen. Vielfach ist es geradezu die sichere, unanfechtbare Thatsache der Pseudomorphosenbildung, die in solchen Gesteinen in viel allgemeinerer Weise beweisend für die Umbildung eintritt, als die nur unter besonders günstigen Umständen erhaltenen Petrafacten in den metamorphisirten Sedimenten. Jahrbuch der königlichen preussischen geologischen Landesanstalt u. Bergakademie für 1883, Berlin, 1884, p. 620.

On page 619 ibid., Lossen in a note gives the following list of references to his former remarks on this same important topic: Zeitschrift der deutschen geologischen Gesellschaft, vol. 21, p. 298, 1869; vol. 24, pp. 706, 707, 763, 1872; vol. 27, pp. 451 and 969, 1875; vol. 29, p. 360, 1877; Sitzungsberichte der Gesellschaft naturforschender Freunde in Berlin, Mch., 1878; Jan., 1880, and Nov., 1883; Jahrbuch der köngl. preuss. geologischen Landesanstalt für 1880, p. 12; für 1881, p. 43, and finally in the Erläuterungen zur geologischen Specialkarte von Preussen und den thüringischen Staaten. Blätter: Harzgerode (p. 79); Wippra (pp. 27, 43); Schwenda (p. 34).

[1] Am. Jour. Sci., 3d ser., vol. 20, 1880, p. 257, and Zeitschr. Kryst. u. Mineral., vol. 5, p. 192.

[2] Quar. Jour. Geol. Soc. London, vol. 43, 1887, Proc. pp. 54-82.

[3] Bull. U. S. Geol. Survey, No. 28, p. 9, 10.

Messrs. Fouqué and Michel-Lévy, of Paris.[1] The exact mineral association and structure of diabase and other basic igneous rocks may be synthetically reproduced by simple dry fusion, and there is no indication whatever that they are ever produced in nature by any other means. The finding therefore of such characteristic structure, even where they have been more or less disguised by subsequent changes, at once furnishes a definite and certain starting point. We know what the original character of the rocks in question was and the conditions under which it was formed; and the careful minute study of the changes which the original component minerals have undergone, when taken in connection with the external physical conditions to which the rock mass has been subjected, can but yield useful results to geological science.

HISTORICAL OUTLINE OF STUDIES ON THE METAMORPHISM OF ERUPTIVE ROCKS.

Notwithstanding the great importance which has always attached to the idea of metamorphism, it is only within recent years that it seems to have been regarded as applicable to any but sedimentary rocks. With Hutton, who may practically be considered the originator of the idea, and with Lyell, to whom we owe the term which describes it, *metamorphism was the gradual consolidation, by means of the earth's internal heat, of sunken and buried strata*, whose original parallel structure was not wholly obliterated by the change. So strong has the power of this tradition become, that it is not easy to overcome it even at the present time. Nor after the discovery and satisfactory explanation of secondary (slaty) cleavage in rock-masses, was the case much better. The distinction between foliation and stratification was accepted as radical, and it was generally conceded that the former was secondarily developed in solid masses as the effect of pressure, and yet we hear of it chiefly in sedimentary rocks—in slates and shales. The eruptive rocks seem to have been regarded as too hard and unchangeable to be affected even by the enormous forces which upheaved a mountain chain. How untrue this is we are daily learning from the study of rocks undoubtedly eruptive, which possess a pronounced schistose structure.

As we now look back over a century of discussion and investigation of metamorphism, the total neglect of eruptive masses, save as an active agent in the change, seems surprising. Daubrée, in his admirable essay on the subject,[2] has much to say of change of structure, and yet he makes no allusion to eruptive rocks as being subjected to it. Delesse, in the second portion of his "Studies of Metamorphism"[3] which treats of regional or normal metamorphism, devotes considerable space to the metamorphism of eruptive rocks, but his conclusions are not such as at the present time deserve attention. He maintains that by some

[1] Synthèse des minéraux et de roches, Paris, 1879.

[2] Études et expériences synthétiques sur le métamorphisme, etc., Mém. présentés par savants à l'Académie des sciences, vol. 17, 1862. Translated in the Smithsonian Annual Report for 1861, pp. 228–304.

[3] Études sur le métamorphisme des roches. Ouvrage couronné par l'Académie des sciences. Paris,

vague process of "general metamorphism" volcanic rocks are changed to plutonic. Thus a trachyte becomes a granite; and a trap, a diorite. The absence of volcanic rocks in the oldest formations is accounted for by the great length of time during which these have been subjected to metamorphosing agencies. The original plutonic rocks are considered to be capable of little or no change.

One of the first truly scientific studies of the metamorphism of eruptive rocks, based purely on careful observation of the facts, was that of Lossen in the Hartz Mountains. Here it was possible to trace the numerous diabase dikes and larger areas of more coarsely crystalline gabbros, along with the schists in which they were inclosed, from their unaltered to their most highly altered form. As early as 1872 he wrote as follows:

I shall begin with igneous rocks which have been altered in situ and with their (final) change into crystalline schists. The fact that massive rocks, which frequently possess a parallel structure as an original feature, may, by metamorphic processes, be converted into foliated, *but not on that account stratified*, beds is incontestable. In this manner granular diabase is converted into lenticularly foliated (flaserig) by the more or less complete passage of the cleavable augite into a scaly aggregate of chloritic minerals. The rock thus assumes a kind of schistose structure, as is often the case in the southwestern Hartz.[1]

The cause of the metamorphism, too, can be seen in some cases to be the eruption of large granite masses; in others, the orographic forces, which had crumpled and upheaved the entire district. Upon this subject Lossen says:

I have often emphasized the significance of those metamorphic regions in which eruptive rocks—interbedded in the schists and like them passively subjected to dislocation and mountain-making forces—have undergone about the same substantial and structural alterations as the inclosing schists; nor is it material whether this result has been accomplished within the contact-zone of some intrusive granitic mass or by dynamic (dislocation) forces properly so called.[2]

Massive rocks may therefore be passively subjected to the influence of either contact or regional metamorphism.

Instances of the former seem never to have received their merited share of attention, and yet they have been mentioned in many different regions. Allport described dolerites which had been altered by adjacent eruptive granites in Cornwall.[3] In France Michel-Lévy has found

[1] Ich beginne mit den in situ umgewandelten Erstarrungsgesteinen und deren Umwandlung zu krystallinischen Schiefern. Die Thatsache, dass durch metamorphische Processe massige Gesteine, die häufig bereits eine ursprüngliche plane Parallelstructur besitzen, in schiefrige, *darum aber noch nicht in geschichtete*, umgewandelt werden, ist unbestreitbar. So gehen die körnigen Diabase dadurch häufig in flaserige über, dass das blätterig brechende augitische Mineral ganz oder theilweise in ein schuppiges Aggregat eines chloritischen Minerals umgewandelt wird, wobei das Gestein eine Art schiefrige Structur annehmen kann, wie dies im Südost Harz nicht selten der Fall ist. (Zeitschr. Deutsch. geol. Gesell., Berlin, vol. 24, p. 763, 1872.)

[2] Merfach bereits habe ich die Bedeutung solcher metamorphischer Gebiete hervorgehoben in welchen zwischen den Schichten eingeschaltete und nur passiv am Faltungs- und Gebirgsbildungsprocesse betheiligte Eruptivgesteine in annähernd demselben Grade wie die daneben anstehenden Schichtgesteine substantielle und structurelle Umwandlungen, sei es in der Contactsphäre der in die Faltung eingreifenden engranitischen Eruptivmassen, sei es durch den Dislocationsprocess schlechthin, erlitten haben. (Jahrb. preuss. geol. Landesanstalt für 1883, p. 619.)

[3] On the metamorphic rocks surrounding the Land's End mass of granite. Quarterly Journal Geol. Soc., London, vol. 32, 1876, p. 422.

similar effects produced in the Cambrian diabases,[1] and Barrois mentions diorites ("diorite modifié") which have been modified by the same cause.[2] Still more recently Brögger has discovered the same class of phenomena in dikes of augite porphyrite which penetrate the strata of the classic silurian region near Christiania.[3]

The most exact and satisfactory accounts of such rocks are, however, those given by Lossen of the diabases which fall within the limits of the Ramberg granite contact zone in the Hartz Mountains.[4] The effect of the granite has been to produce alterations in the eruptive diabases quite analogous to those usually brought about by orographic forces. The augite has been changed to uralite, which surrounds the core of the original mineral in a double zone, the inner one being colorless and dotted with magnetite, while the outer one is composed of a more compact, green, and pleochroic hornblende.[5] The labradorite of these diabases has been saussuritized; their ilmenite has been changed to sphene (leucoxene) and their pyrite to pyrrhotite. Biotite and garnet have also been occasionally developed. The characteristic diabase structure is recognizable so long as any of the augite or labradorite substance remains.

If the results described by Lossen are in reality wholly due to the influence of the intrusive granite mass, then we see that the similarity between the effects produced by contact metamorphism and regional metamorphism is just as close in the case of eruptive rocks as it is in that of sedimentary beds. The connection which exists between regionally metamorphosed areas and the disturbances to which such areas have been subjected appears to be a constant one. Indeed, aside from the local influences of intrusive masses, the amount of metamorphism may be said to be in all cases proportional to the pressure or strain to which the rock in question has been subjected. The recent recognition of this fact has brought into favor the term "*dynamic metamorphism*,"[6] which, in a way, expresses the agency or process to which the change may be attributed.

Rocks are not metamorphosed by pressure alone, and yet the importance of this agency would appear to be greater than that which has commonly been assigned to it. Other factors, especially heat and moisture, have also played an important part in the changes, but their efficacy is in large measure due to the direct results of pressure upon

[1] Sur les roches éruptives basiques Cambriennes du Mâconnais et du Beaujolais. Bull. Soc. géol. France, 3 series, vol. 11, 1883, pp. 273-303.

[2] Le granite de Rostrenen, ses apophyses et ses contacts. Annales Soc. géologique du Nord, 1884, vol. 12.

[3] Spaltenverwerfungen in der Gegend Langesund-Skien. Nyt Mag. for Naturvidenskaberne, vol. 23, 1884, pp. 253-419.

[4] Ueber den Ramberg Granit und seinen Contact-Hof. Erläuterungen zu Blatt Harzgerode der geologischen Specialkarte von Preussen und der thüringischen Staaten. Vide also Jahrb. kön. preuss. geol. Landesanstalt für 1883, pp. 619-642; für 1884, pp. 56-112, and pp. 525-545.

[5] For an illustration of this structure, see Bull. U. S. Geol. Survey, No. 28, 1886, Pl. I. Fig. 2.

[6] "Mechanical metamorphism" of Heim and Baltzer, "Dislocation-M." of Lossen, "Dynamical-M." of Rosenbusch, "Stauungs-M." of Credner, "Pressure-M." of Bonney.

the solid rock-mass. The crushing of rocks along fault or shearing planes allows here of the ready circulation of moisture and of a consequent increased distribution of heat. Rocks are hence most altered along such planes. The almost universal effect of such a crushing is made apparent by a microscopic examination of rocks which have been subjected to enormous pressure. We shall have occasion to cite numerous instances of this in the sequel. For the present we will state the three different modes in which an eruptive rock is altered when it undergoes regional or dynamic metamorphism, and mention the work of those who have been particularly successful in illustrating the action of all or any of them.

The three ways in which a massive crystalline rock may be modified by the action of orographic forces are:

I. Macro-structural; i. e., it may have its external structure (morphology) changed so as to become schistose or foliated.

II. Micro-structural; i. e., it may have its internal or microscopic structure (histology) wholly changed, either with or without an alteration of the last-mentioned sort.

III. Mineralogical; i. e., there may be a change in the nature of one or more of the component minerals, either with or without a change in the chemical composition of the rock as a whole.

Of course, any one of these kinds of change may be produced in a rock-mass alone, or any two, or even all three, may exist simultaneously in any relative degree of intensity.

Macrostructural Metamorphism.—It had already long been recognized that transversal or slaty cleavage could be produced in sedimentary beds by mechanical force,[1] when A. Heim, in his work on the "Mechanism of Mountainmaking," published in 1878,[2] directed attention to an almost new line of geological work, by showing in a very general way how the orographic forces effect the deformation of rock-masses. He insisted upon three main points:

(*a*) That the rocks were solid and rigid when they were acted upon.

(*b*) That by a moderate pressure, they are torn asunder and the thus formed open fissures ("klaffende Risse") are subsequently filled by material segregated from the rock ("adern"). If the mass is plastic rather than brittle, the strain is relieved by numerous slicken-sides ("Rutschflächen") ("*Umformung mit Bruch*").

(*c*) That by the most intense pressure this action becomes infinitely small or molecular, i. e., the form is altered without rupture ("*Umformung ohne Bruch*").

Heim lays great stress upon the fact, already emphasized by Suess,[3] that the massive or crystalline rocks which form the center of the Al-

[1] On slaty cleavage and allied rock-structures with special reference to the mechanical theories of their origin. By Alfred Harker. Rept. fifty-fifth meeting Brit. Assoc. Adv. Sci., in 1885, pp. 813–855, 1886.

[2] Untersuchungen über den Mechanismus der Gebirgsbildung im Anschluss an die geologische Monographie der Tödi-Windgällen-Gruppe. Basle, 1878. Vol. 2.

[3] Die Entstehung der Alpen. Wien, 1875.

pine "massivs" were not themselves in any way instrumental in the elevation of the mountains. He gives an elaborate proof that these were solid long before the elevation; and were only *passively* subjected to the upheaving force, in the same way as the overlying sediments. Heim does not, however, seem to apply his laws of mechanical deformation to these crystalline rocks, as he might well have done, but regards their schistose or banded structure as probably an original character.

Other geologists were not long in recognizing the mechanical deformation of massive as well as sedimentary rocks. Daubrée is struck by the frequent gradual passage of massive rocks into schistose varieties of the same composition. He says that, in spite of his own strong leanings toward the "metamorphic theory," he can not possibly regard such a schistose structure as any sign of original stratification but must consider it as secondarily produced in the eruptive mass by pressure. He is, however, inclined to believe that this result was attained before the eruptive rock had wholly solidified.[1] H. H. Reusch, from his studies of the rocks near Bergen, in Norway, is also convinced that the frequent banding and gneissic structure in granite is secondary and a product of pressure, like slaty cleavage. Like Daubrée, he too thinks that it was accomplished while the rock was still somewhat soft, at the time of the faulting and dislocation to which the granite owed its own elevation, in a plastic state.[2] This idea that such pressure deformation could only take place in softened or in unsolidified rocks was particularly dwelt upon by Carl Friedrich Naumann. How thoroughly the objections to the deformation of rigid rock masses, as far as sedimentary deposits are concerned, are answered by the facts observed by Heim, we have already seen. The assumption of an identical process for the highly crystalline massive rocks seems, at first, to present great difficulties, but observations in all parts of the world are daily proving its necessity.

In 1879, Rothpletz[3] showed how the actinolite, or so-called greenschists near Hainichen, in Saxony, had been brecciated by pressure and the fragments shoved along more or less upon each other, so as often to produce an imperfect schistose structure. This, which has a close analogy to certain macrostructural modifications of the Lake Superior greenstones to be described in subsequent pages, allowed, as Rothpletz remarked, a much increased chemical action, which tended to alter the character of the rock. A. Baltzer, in his monograph on the Finsteraarhorn,[4] published in 1880, expresses himself as decidedly in favor of a mechanical metamorphism of the interior crystalline rocks. He says on page 244 of his work:

[1] Études synthétiques de géologie expérimentelle. Paris, 1879, p. 432.

[2] Die fossilien führenden krystallinischen Schiefer von Bergen in Norwegen. Deutsche Aufgabe von R. Baldauf, 1883, pp. 129, 130.

[3] Ueber mechanischen Gesteinsumwandlungen bei Hainichen in Sachsen. II. Die Breccienbildung des Aktinolithschiefers von Hainichen. Zeitschr. Deutsch. geol. Gesell, 1879, Vol. 31, p. 374.

[4] Die mechanische Contact von Gneiss und Kalk im Berner Oberland. Beiträge zur geologischen Karte der Schweiz. XX. Lieferung. Bern, 1880.

I base my assumption that the parallelism of the mica-scales in abnormally stratified gneiss is conditioned by pressure, upon this transverse foliation. Just as slaty-cleavage is generated in the younger sedimentary rocks by pressure and mechanical deformation, so is it also in the crystalline schists. This may be proved in the case of the last named rocks, if other evidence is lacking, by its parallelism with the undoubted cleavage in contiguous sediments.[1]

Similar ideas have been more or less clearly expressed by Kjerulf, Brögger, Stapff, and other geologists, but one of the most important contributions to our knowledge of this, as well as of other phases of mechanical metamorphism, was made in 1884 by Prof. Johannes Lehmann in his work on the origin of the crystalline schists.[2] That author has collected an immense number of observations from Saxony, Bavaria, and Bohemia—especially in the "Granulite" district of the first named country, upon the detailed study of which he has spent many years. From these observations Lehmann reaches certain general conclusions of importance with reference to the mechanical metamorphism of solid massive rocks. These are stated in chapters 16 and 17 of his work. He regards gneiss as simply a structure form of granular feldspathic rocks, and according to the composition of these there may occur granitic gneiss, syenitic gneiss, dioritic gneiss, gabbro gneiss, etc. He thinks that the essential parallel structure of gneiss may be, but very rarely is, original. He finds no indication that any true gneisses were once sedimentary deposits, but he considers them all as igneous rocks ("Erstarrungsgesteine"), which, as a general thing, have acquired their present structure by stretching ("Streckung") in a solid state. Moreover, gneiss exhibits only the first stage of such a mechanical metamorphism. If the action of this process is more intense, finer grained and more evenly banded rocks result, which the author designates as granulite and felsite schist. According to Lehmann, therefore, all the massive crystalline rocks are subject to alterations in their structure through great pressure or tension. They become banded or schistose in proportion to the intensity of this action.

The observations of many workers in various regions since the publication of Lehmann's conclusions have tended to substantiate them. Mr. Hatch[3] has shown the secondary development of a schistose structure in the gabbros of the Tyrol, and the same thing has been done for the gabbros near Baltimore, Maryland.[4] Results very closely resembling those of Lehmann have recently been secured by Mr. J. J. H. Teall in the gabbro region of the Lizard, Cornwall, England.[5] This

[1] Auf diese transversale Schieferung gründe ich die Annahme dass der Parallelimus der Glimmerblättchen im anormal gelagerten Gneiss ebenfalls von Druckschieferung herrührt. Wie in den jüngern Sedimentgesteinen durch Druck und mechanische Umformungsprozesse transversale Schiefe ung entstand, so auch in den krystallinischen Schiefern. Bei letzteren kann sie, in Ermangelung anderer Anhaltspunkte, durch den Parallelismus mit einer unzweifelhaften Schieferungsrichtung in den angrenzenden Sedimenten nachgewiesen werden.

[2] Untersuchungen über die Entstehung der altkrystallinischen Schiefergesteine, etc., with Atlas of photographs. 4°. Bonn, 1884.

[3] Tschermak's mineral. u. petrog. Mittheil.. vol. 7 (1885), p. 75.

[4] Bull. U. S. Geol. Survey, No. 28.

[5] Geol. Mag., London, November, 1886.

investigator derives proof that the alteration in structure was accomplished after complete solidification from the relation of the rock to fault-planes. He says:

A rock must necessarily be solid before it can be faulted. Now, we find at Pen Voose near Landewednack, that massive gabbro passes over into gabbro schist at a fault-plane, and that the foliation in the gabbro is such as would be produced by a shearing motion parallel with the fault-plane. Taking all the facts into consideration, we appear to be justified in concluding that the foliation in the Lizard gabbros is the result of pressure or regional metamorphism.

C. Schmidt has also recently given us the results of his studies of certain eruptive porphyries in the central Alps, especially in the Windgällen group, the district particularly studied by Heim.[1] These, like the surrounding sediments, have been subjected to enormous pressure and strains and thereby have had developed in them a pronounced schistose structure, becoming in some instances veritable felsite schists. Still more recently H. H. Reusch has communicated his observations in the regionally metamorphosed district of Hardangerfjord, on the west coast or Norway.[2] Here he finds dikes of all sorts of eruptive rocks, both acid and basic, all rendered secondarily schistose parallel to the planes of the inclosing schists, without reference to the direction of the dikes themselves. This, therefore, can not possibly be due to either flow or cooling, but must be the result of pressure. Ch. E. Weiss observed the same thing in the quartz porphyry dikes of Thal, in Thuringia.[3]

Prof. T. G. Bonney, in his annual presidential address to the Geological Society of London (February, 1886), deals with the subject of metamorphism in general, and has much to say about the structural changes induced in holocrystalline massive rocks by pressure[4]. He distinguises between "*stratification-foliation*" and "*cleavage-foliation*," the latter being always secondarily produced by pressure.[5] This same cause also in some cases may produce a false bedding parallel to the cleavage-foliation, almost exactly similar to the bedding of sedimentary rocks, although of a totally different origin, and to this he applies the name "pseudostromatism."[6]

Microstructural metamorphism.—The statement of Heim that under sufficient pressure rock-masses became plastic, i. e., that they could be bent and crumpled by a true molecular movement within the mass, without rupture, seems to have been based entirely on a macroscopical study of exposures and specimens. Rocks, and even their constituent minerals, certainly do appear to the unaided eye to be stretched and contorted without any break in their continuity. Whether, however, this effect is accomplished by a truly molecular movement, as in a viscous body,

[1] Neues Jahrbuch für Mineralogie, etc., Beilageband 4, p. 388, 1886.
[2] Ibid., Beilageband 5, p. 56, 1887.
[3] Zeitschr. Deutsch. geol. Gesell., vol. 36, 1884, p. 858.
[4] Quar. Jour. Geol. Soc. London, vol. 42, 1886, Proc., p. 95.
[5] Ibid., p. 64.
[6] Ibid., p. 65.

or by a breaking or crushing of the component crystals with a movement in the mass before it is recemented, is something that can not be well decided by the unaided eye. Such authorities as Gümbel[1] and Pfaff[2] at once took exception to the conclusions of Heim, and stated it as their conviction that, strictly speaking, there was no such thing as the deformation of rocks without rupture. Baltzer[3] could not decide between the conflicting views, but thought there was probably truth in each. The microscopical study of such bent and contorted rocks seems to show that the explanation of Gümbel is generally the true one. This was emphasized by J. Lehmann.[4] He calls attention to the fact that the conception of plasticity is not a simple one. We speak both of wax and of wet clay as "plastic," and yet the movement of the homogeneous body is different from that in the heterogeneous substance. In each the process of the deformation escapes the eye and the results appear the same; but in reality the first is molecular, the second caused by the slipping of the component particles (kaolin scales) over each other. In rocks the "plasticity" is of the second kind. Lehmann[5] says:

> When rock-deformation has been accomplished by a breaking and sliding of the individual constituents upon each other, I think that I am still justified in calling it a deformation without rupture, provided the continuity of the rock-mass itself has been preserved and no fissures have been formed. * * * I recognize only that as rock-deformation with rupture when fissures, even though microscopic, traverse the rock independent of the individual constituents.[6]

Again he says:[7]

> A plastic molding of the separate constituents, as is assumed by Heim, I have nowhere been able to discover. On the other hand, the maximum of resistance which a crystalline grain can offer to bending or crushing is very soon reached, and then ensues a pulverizing or chemical solution.[8]

Lehmann also particularly emphasizes the importance of the very much increased chemical action which such a crushing of the rock components permits. This had heretofore been almost overlooked by all the students of dynamic or mechanical metamorphism except Lossen. The ease with which a ready circulation and changed physical condition allow the destruction of certain chemical compounds, and the im-

[1] Das Verhalten der Schichtgesteine in gebogenen Lagen. Sitzungsberichte der kön. bayrischen Akademie. Math.-phys. Classe, vol. 4, p. 596, 1880 (reviewed by Rosenbusch in the Neues Jahrbuch für Mineral., 1882, vol. 1, Referate, p. 221).

[2] Der Mechanismus der Gebirgsbildung. Heidelberg, 1880, p. 140.

[3] Die mechanische Contact von Gneiss und Kalk im Berner Oberland, Bern, 1880, p. 240.

[4] "Untersuchungen über die Entstehung der altkrystallinischen Schiefergesteine, etc.." Chap. XVI.

[5] Ibid., p. 245.

[6] Ich glaube sogar mit Recht eine Gesteinsformung, bei welcher nur die einzelnen Gemengtheile zerspalten und sich an einander verschieben, als eine bruchlose bezeichnen zu könen, wenn das Gestein seinen Zusammenhalt bewahrt hat und keine das Gestein durchsetzenden Risse vorhanden sind. * * * Eine Gesteinsformung mit Bruch erkenne ich erst dann an, wenn Risse, und mögen es auch mikroskopische sein, unbekümmert um die Einzelgemengtheile das Gesteinsgewebe durchsetzen.

[7] Ibid., p. 249.

[8] Eine plastische Formung der Einzelgemengtheile, wie sie Heim annehmen zu müssen glaubt, habe ich niemals gefunden; vielmehr erreicht die Biegung oder Zusammendrückung eines Krystallkorns sehr bald das Maximum und erfolgt dann eine Zertrümmerung beziehungsweise auch eine chemische Auflösung.

mediate formation of others out of their elements, is calculated to preserve the continuity of the rock-mass in spite of extensive stretching or compression.

Such chemical changes will form the subject of the following section. Here we are concerned only with the mechanical deformation of the elementary minerals.

The effects of pressure will naturally be first noticeable upon an elastic mineral like mica. A bending of the lamellæ is well known to result frequently from even the slight movement of an eruptive magma before its complete solidification. Wherever, therefore, so sensitive a mineral presents no pressure effects when more brittle substances show them, it is fair to assume that the mica has been secondarily developed during the action of the pressure.

Harder minerals, like augite or feldspar, under the first action of strain, before their cohesion is overcome, appear to have twinning lamellæ developed in them parallel to certain planes—and most abundantly where the strain is the most intense. To this succeeds a cracking of the crystal, with often a considerable separation of the parts and a filling of the interstices by newly deposited substance.[1] A still more intense pressure accompanied by a shearing stress seems to produce a regular granulation of the larger crystals, so that around their edge they pass into a mosaic-like aggregate of fine interlocking grains. This process in the case of augite, as in the Saxon "Flaser-Gabbros," is attended by uralitization, or the production of secondary amphibole. The resulting structure, in which larger grains are separated by a finer mosaic, has been called by Törnebohm, who observed it in certain Swedish granites, "mortar-structure" ("Mörtel-Structur").[2] This granulation, with increasing strain, may extend farther and farther inward until finally the entire crystal is replaced by a fine mosaic of interlocking grains. When produced under the influence of sufficient pressure, it may, of course, give rise to a pronounced banded or schistose structure.

The action of strain upon the hardest and most brittle of the rock-forming minerals—quartz—seems to result in cracking and breaking, rather than in bending it. Crystals which appear in hand-specimens to be stretched out into lenses, are shown by the microscope to be composed of smaller grains, more or less different in their optical orientation. Of this mineral Lehmann says:[3]

> The phenomena which the quartz of stretched rocks exhibit manifest themselves under the polarizations microscope in the unequal extinction of different fields, and

[1] See Lehmann's Atlas, Pl. 6, Figs. 3, 6, and Pl. 21, Figs. 3, 6.

[2] Några ord om granit och gneis. Geol. Föreningens Stockholm Förhandl., vol. 5, pp. 233–248, 1880–81 (review in the Neues Jahrbuch für Mineral., 1881, vol. 2, Referate, p. 50). Törnebohm, in this paper, considers this as an original structure. Kjerulf designates all such dynamic changes as are manifested in a movement among the fragments of broken crystals as "*Kataklas-structur.*" He distinguishes three grades of intensity. See Grundfjeldsprofilet ved Mjøsens sydende. Nyt Mag. for Naturvidenskaberne, vol. 29, p. 215, 1885 (review Neues Jahrbuch für Mineral., 1886, vol. 2, Referate, p. 244). See also Rosenbusch: Mikros. Physiog., vol. 2, 2d ed., p. 42, 1887.

[3] Untersuchungen über die Entstehung der altkrystallinischen Schiefergesteine, etc., p. 250.

then in a somewhat more exact separation of these fields. We imagine that we can detect sharp boundary lines without being able to certainly prove their existence (and in reality they are due merely to tension). Finally, however, the individual grain does really break up into separate interlocking parts, which at first are but slightly changed in their orientation. Nevertheless, toward the edge and in the more compressed portions these parts are quite irregularly orientated and participate in the composition of the ground-mass. True bending of quartz is unknown to me. It is shattered very easily, and, as it seems, is as readily subject to chemical solution.[1]

Prof. Ch. E. Weiss, of Berlin, describes remarkably deformed quartzes in the schistose porphyries occurring in the almost horizontal mica schist near Thal in Thuringia.[2] This rock forms dikes which cut across the bedding of the schist and send apophyses in a horizontal direction between its layers. The schistose structure of the porphyry was formerly considered to be a flow structure, but Weiss has shown that this can not possibly be, as it runs in every case *parallel to the bedding of the mica-schist without reference to whether this is parallel or perpendicular to the walls of the dike.* The porphyritic quartz crystals in these rocks are drawn out into long, pear-shaped or tadpole-like ("kaulquappenähnlich") forms, which follow the direction of the schistose structure. This is accomplished sometimes with, sometimes without, a rupture of the quartz substance, and produces what Lossen calls tailed-quartzes. ("Schwänzchen-quarz.")[3]

It is remarkable that the porphyritic feldspar crystals of these rocks have suffered far less deformation than the much harder quartzes, an observation which, as we shall see, is abundantly substantiated in the schistose porphyries of the Lake Superior region. The phenomena exhibited by the Thuringian rocks, although left without explanation by Weiss, are referred without hesitation by Rosenbusch to the effects of dynamic metamorphism.[4]

Rosenbusch also remarks that, as a rule, the peripheral granulation ("randliche Kataklase"), characteristic of the coarse-grained, granitic rocks, is wanting in the porphyries. This he attributes to the structure, for in the granular rocks under great pressure the grains rub against each other, while in porphyritic rocks the larger crystals are imbedded in a homogeneous matrix, so that they are either only optically disturbed or completely pulverized.[5]

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[1] Die Erscheinungen, welche der Quarz gestreckter Gesteine zeigt, bekunden sich unter dem Polarisationsmikroskop in einem ungleichen Dunkelwerden verschiedener Felder, dann in einer schärferen Abgrenzung derselben; man glaubt Begrenzungslinien zu sehen, ohne dass solche thatsächlich nachzuweisen wären—sie beruhen wohl nur auf Spannungen—endlich zerfällt das einheitliche Korn aber wirklich in einzelne, zackig begrenzte Theile, die zunächst nur wenig aus ihrer Lage gedreht erscheinen; gegen den Rand des Korns und in stärker gepressten Theilen jedoch wirr durcheinanderliegen und an der Zusammensetzung der feinkörnigen Grundmasse sich betheiligen. Eigentliche Biegungen von Quarzen sind mir nicht bekannt; er zerstückt und zerfällt sehr leicht und erliegt wie es scheint ebenso leicht einer chemischen Auflösung.

[2] Jahrbuch preuss. geol. Landesanstalt für 1883, pp. 213-237, Berlin, 1884; and Zeitsch. Deutsch. geol. Gesell., vol. 36, 1884, p. 858. Cf. J. G. Bornemann: Jahrbuch preuss. geol. Landesanstalt für 1883, pp. 383-409, Berlin, 1881.

[3] Zeitsch. Deutsch. geol. Gesell., vol. 34, 1882, p. 678.

[4] Die massigen Gesteine, 2d ed., 1886, p. 214.

[5] Ibid., p. 413.

Dr. C. Chelius describes compressed and schistose granite porphyries from the northern portion of the Odenwald (Hesse-Darmstadt). In these the ground-mass is quite fine-grained, but where small areas of it have been protected, as it were, by large porphyritic crystals *it has nearly twice as coarse a grain.*[1]

It would appear to be quite generally the case that porphyritic massive rocks, when subjected to great pressure, develop the so-called "Augen structure." The larger crystals are only partially pulverized, and have on either side of them, in the direction of the schistose structure, a mosaic of their own débris, arranged like the "crag-and-tail" of a glaciated ledge. This has been observed and admirably described by Lehmann[2] in the Saxon granulites, by Teall[3] in the gabbros of the Lizard district, Cornwall, and by Bonney.[4]

Mineralogical metamorphism.—This is undoubtedly the most important phase of metamorphism in eruptive as well as in sedimentary rock masses. It always accompanies such mechanical deformation—whether macroscopical or microscopical—as has been already described; but, while such dynamic processes may greatly facilitate chemical action or molecular rearrangement, they are by no means always necessary to bring them about. The adjustment between the chemical combinations and external conditions is so delicate in the inorganic world as to make the difference, in this respect, between minerals and living organisms seem rather one of degree than of kind. This point has been elaborated by Professor Judd in his recent annual address before the Geological Society of London (February 18, 1887).[5] Wadsworth[6] has also insisted that the changes in the mineral world are due to the passages from states of less stable to those of more stable equilibrium; but, as Judd justly remarks, the cycle of changes may be infinite because the stability of a compound depends upon its surrounding conditions. With a change of these, a state which was once stable becomes unstable. No student of mineralogy can fail to appreciate the extreme delicacy of the equipoise. Any one who has produced artificial twinning-lamellæ in feldspar or calcite, or watched sulphur or boracite or tridymite or leucite pass from one modification into another, must acknowledge the importance of paramorphism in the formation of rocks. But changes of minerals accompanied by changes in the chemical nature of the compound are still more common. These may consist (1) in the breaking up of one molecule into two or more, with but little replacement of substance, as in the formation of saussurite from labradorite, or of β spodumene (albite + eucryptite) from spodumene; or (2) in a reaction which takes place between two contiguous minerals, each supplying a part of

[1] Notizblatt des Vereins für Erdkunde zu Darmstadt, 4. Folge, Heft 5, 1885, p. 29.
[2] Untersuchungen über die Entstehung der altkrystallinischen Schiefergesteine, etc. Bonn, 1884.
[3] Geol. Mag., London, Nov., 1886.
[4] Presidential address to the Geological Society, Feb., 1886., Quart. Jour. Geol. Soc. London, vol. 42, Proc., p. 96.
[5] See also the writer, Pop. Sci. Monthly, Sept., 1889.
[6] Nature, March 3, 1887, p. 417.

the substance necessary to form a new compound of intermediate composition, more stable for the then existing conditions than either. Such a case is the formation of a hornblende zone between crystals of olivine or hypersthene and plagioclase, or of the so-called "kelyphite" zone between pyrope and serpentine; (3) in more complicated and less easily understood chemical reactions, like the formation of garnet or mica from materials which have been brought together from a distance and under circumstances of which it is at present impossible to state anything with certainty.

All such changes involving an actual change in the chemical composition are best designated in contrast to those produced by paramorphism, as metasomatic.[1]

Of course all of these metamorphic changes of a mineralogical character—whether paramorphic or metasomatic—may go on in all conceivable proportions in a rock mass at the same time. They are often accompanied by changes in the original structure of the rock, but not of necessity, although such changes of structure can not be accomplished without chemical alteration.

Chemical changes in minerals and rocks have occupied the attention of mineralogists and chemists from the beginning of the century, and yet it is almost exclusively in sedimentary rocks that such studies have been carried on. Only within recent years have the mineralogical metamorphoses which take place in eruptive rocks commenced to receive their proper share of consideration. Lossen, Törnebohm, and J. Lehmann were the first in Europe to recognize the importance of such investigations; while it will ever remain one of the most signal services which Dr. Wadsworth has rendered to petrography that he was the first in America to fully grasp their significance and to emphasize it.

It would be quite beyond the purpose of the present paper, even if it were possible, to give a complete summary of all that has been done on the subject of chemical changes in eruptive rocks. In this place the attempt will be made only to trace out historically some of the more important alterations which have a direct bearing upon the rocks forming the subject of this investigation. Important and wide-spread phases of the metamorphism of eruptive rocks—such, for instance, as serpentinization—which are not exemplified within the area studied will not be here considered. On the other hand, minor details or local modifications of well known and universally recognized processes will be elaborated in the course of the special petrographical descriptions (Chapters II–V) and summarized in Chapter VI.

The points which will be historically considered in this chapter are the following:

(1.) *Uralitization*, or the secondary origin of hornblende, both fibrous and compact, from pyroxene.

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[1] This term is preferred to *methylosis* of King and Rowney ("An old chapter of the geological record with a new interpretation;" London, 1881), and Bonney (Quart. Jour. Geol. Soc., London, vol. 42, 1886, Proc., p. 59), and to *metachemic* of Dana (Am. Jour. Sci., 1886, 3d series, vol. 32, p. 70), because it is at present so much more widely used and hence so much more intelligible.

(2.) *Chloritization.*
(3.) *Epidotization.*
(4.) *Formation of the viridite (chlorite) epidote aggregate.*
(5.) *Saussuritization.*
(6.) *Formation of the albite mosaic.*
(7.) *Sericitization.*
(8.) *Alterations of titanic-iron.*

Uralitization.—Ever since the classic record of observations made by Gustav Rose in the Ural Mountains in 1830,[1] the fact has remained undisputed that pyroxene sometimes changes to an aggregate of amphibole needles which often preserve by their arrangement the original augitic form. It was not long before other similar occurrences were discovered, notably in Scandinavia and the Tyrol. Still, these localities were regarded as exceptional, and it was impossible that the full geological importance of Rose's uralite should be appreciated without the aid of the microscope. With the help of this instrument it was soon discovered that the smaragdite of the saussurite gabbros or euphotides was a secondary hornblende which had originated from the diallage. As the number of observers and observations increased, instances of the undoubted passage of every sort of pyroxene into a fibrous amphibole grew constantly more and more abundant. It would be useless to attempt to trace out these discoveries in detail. It is enough merely to mention the names of Rose, Vom Rath, Fischer, Hagge, Zirkel, Von Lasaulx, Rosenbusch, Törnebohm, Svedmark, Sjögren, Becke, Kloos, Michel-Lévy, Allport, Phillips, Teall and Hatch, in Europe, and of Hawes in this country, to recall the accuracy and value of the facts recorded, while among the first to see further than mere facts and to grasp the full geological significance of this wide-spread change may be placed Lossen, Lehmann, Reusch, Wadsworth and Irving.

The alteration of pyroxene to hornblende is almost universally alluded to as paramorphism, and such, indeed, it may be in some instances. Still, many investigations go to prove that it is very often, perhaps always, accomplished by chemical change. The original uralite of Rose was too soft and hydrous to be compared with hornblende. The studies of Forschhammer, Rose,[2] and Svedmark[3] showed that when augite changed to fibrous hornblende, magnetite and often calcite was separated out between the needles. A recent opinion by Rosenbusch on this point is as follows:

> This uralitization can hardly be regarded as a simple act of molecular rearrangement; we should rather expect that a part of the lime contained in the augite would pass into other combinations, and, in fact, epidote is an almost constant companion of uralite.[4]

[1] Poggendorff Annalen, vol. 22, 1831; vol. 31, 1834, p. 617; also Reise nach dem Ural, vol. 2, p. 342.
[2] Zeitschr. Deutsch. geol. Gesell. Berlin, vol. 16, 1864, p. 6.
[3] Neues Jahrbuch für Mineral., 1877, p. 99; Mikros. Physiog., vol. 2; 2d ed., p. 185; vol. 1, p. 472.
[4] Diese Uralitisirung kann nicht wohl ein einfacher Act molecularer Umlagerung sein, es ist viel mehr zu erwarten, dass ein Theil des Kalkgehalts des Augits in andere Verbindungen übergehe und thatsächlich ist Epidot ein nahezu constanter Begleiter des Uralits.

Dr. B. Harrington, of Montreal, has carefully analyzed three stages of alteration between pyroxene and a secondary fibrous hornblende resulting from it, and has found that during the change there has been a great loss of lime and a gain of magnesia, silica, and the alkalies.[1] The specimen investigated was one of the excellent examples of uralite from the apatite mines near Ottawa, Canada, similar to those named by Thomson "Raphilite."[2]

Mr. J. J. H. Teall has also recently discussed this point in connection with his studies of the alteration of the Scourie dike,[3] and is of the opinion that the oxidation of iron from the ferrous to the ferric state is incident to the change of augite to hornblende.

While the alteration of almost any pyroxene into fibrous hornblende has now become a universally recognized fact, the possibility of the change of this mineral directly into compact hornblende is by no means so generally admitted. So admirable an observer as J. H. Kloos has recently based his distinction between primary and secondary amphibole in the Black Forest gabbros entirely upon their compact or thin fibrous character.[4] Still, the work of many investigators shows that this is by no means a reliable criterion in all cases.

Svedmark found in 1876 that the pyroxene of the Vaksala porphyry passed into an aggregate of stout, compact amphibole needles.[5] In 1877 Streng described compact brown hornblende in the Minnesota gabbros, which he considered to have originated from the diallage;[6] and in 1878 Dr. George W. Hawes described and figured similar occurrences in certain New Hampshire rocks.[7] In 1880 appeared accounts by Irving, and in 1882 by both Irving and Van Hise, of compact brown hornblende originating from diallage.[8] In 1880 C. von John described the alteration of diallage to compact brown hordblende in the olivine gabbro of Bosnia.[9] In 1883 Hj. Sjögren regarded the irregular spots of compact brown hornblende which occur in and around the pyroxene of the wernerite or dipyre-diorite of Bamle in Norway as produced by a molecular rearrangement of the pyroxene substance.[10] In 1884 similar observations were made by myself in certain pyroxenites of the "Cortlandt Series," occurring at Montrose Point on the Hudson River; also in the so-called "black granite" (gabbro) from Addison, Me., and in rocks from the apatite regions of Canada.[11] In the same year (1884)

[1] Geol. Survey, Canada. Report of progress for 1878–79. Appendix G, p. 23.

[2] Outlines of Mineralogy, Geology, etc., London, 1836, vol. 1, p. 153.

[3] Quart. Jour. Geol. Soc. London, vol. 41, 1885, p. 137.

[4] Neues Jahrbuch für Mineral., Beilage-Band 3, 1884, pp. 32, 33.

[5] Geol. Föreningens Stockholm Förhandl., 1876, pp. 151–164; Neues Jahrbuch für Mineral., 1877, p. 99.

[6] Neues Jahrbuch für Mineral., 1877, pp. 133, 240; Am. Jour. Sci., Dec., 1884, p. 464.

[7] The Geology of New Hampshire, vol. 3, 1878, part iv, Mineralogy and Lithology, pp. 57, 206, pl. vii, fig 1.

[8] Geol. Wisconsin, vol. 3, (1880) p. 170; vol, 4, (1882) p. 662. See also Geol. Wisconsin, vol. 1, 1883, p. 321, and Am. Jour. Sci., 3d series, vol. 26, p. 29, 1883.

[9] Grundlinien der Geologie von Bosnien-Herzegovina, Wien, 1880. (Cf. Neues Jahrbuch für Mineral., 1881, vol. 2. Referate, p. 353.)

[10] Geol. Föreningens Stockholm Förhandl., vol. 6, p. 447, 1883. (Cf. Neues Jahrbuch für Mineral. 1884, vol. 1. Referate, p. 81.)

[11] Am. Jour. Sci., 3d series, vol. 28, Oct., 1884, p. 261.

A. Schenck quotes in his Inaugural Dissertation a statement made by von Lasaulx in 1878, that pyroxene passes first into fibrous and subsequently into compact brown hornblende.[1] Schenck himself observed in the Rimberg diabase from the upper Ruhr Valley that the reverse of this was true, i. e., that the pyroxene passed first into compact brown, and this subsequently into fibrous green hornblende.[2]

The secondary hornblende, so well described and figured by Teall in the Scourie dike, is decidedly compact in its nature,[3] nor is that derived from the paramorphism of the diallage in the Saxon "flaser-gabbros," according to the observations of J. Lehmann, less compact.[4] Such eminent authorities as Lossen[5] and Rosenbusch[6] also allow that there is no doubt that compact basaltic hornblende occasionally results through the direct paramorphism of diallage, or even orthorhombic pyroxene. The chemical composition of the original mineral undoubtedly largely conditions the nature of the resultant product. This is shown by the observations of von John in the Flysch-gabbros of Bosnia, where brown hornblende resulted from dark and green hornblende from pale diallage.[7]

These facts are dwelt upon here somewhat in detail because, as will been seen in the sequel, they have possibly an important bearing on a large part of the Menominee River greenstones.

It is not intended, of course, to imply by the above statements that true parallel growths of primary augite and primary brown hornblende may not occur, as held by both Lossen and Rosenbusch (loc. cit.). Such parallel growths would have the closest possible resemblance to alteration forms, and I can not escape the conviction that the tendency of future studies will be to attribute a secondary origin to more and more of such intergrown brown hornblende.

The derivation of fibrous or actinolitic hornblende, quite identical in all respects with uralite, from compact hornblende (whether brown or green) seems hitherto to have been much neglected. Inostranzeff in 1879 described Russian diorites in which the original hornblende had passed into secondary actinolite, as well as into biotite, chlorite and talc.[8] Becke also, in 1882, mentions uralite formed from both pyroxene and compact, primary hornblende, in the kersantite of the "Niederoesterreichisches Waldviertel."[9]

Descriptions have also been given by myself of compact brown hornblende changing into the green fibrous variety in the Baltimore gabbros.[10]

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[1] Verh. d. naturh. Vereins d. pr. Rheinl. und Westf., 1878, p. 171, pl. IV, fig. 4.

[2] Die Diabase des oberen Ruhrthals, etc., Inaugural-Dissertation. Bonn, 1884, p. 41.

[3] Quart. Jour. Geol. Soc. London, vol. 41, p. 137, 1885, pl. II, fig. 2.

[4] Ueber die Entstehung der altkrystallinischen Schiefergesteine, etc. Bonn, 1884.

[5] Jahrbuch preuss. geol. Landesanstalt für 1884, p. 537, Berlin, 1885.

[6] Mikros. Physiog., 2d ed., vol. 2, 1887, pp. 141, 209.

[7] Ueber kryst. Gest. Bosniens und der Herzegovina in Grundlinien der Geol. von Bosnien-Herzegovina, Wien, 1880 (ref. Neues Jahrbuch für Mineral., 1881, vol. 2. Referate, p. 353).

[8] Studien über metamorphosirte Gesteine im Gouvernement Olenez. Leipzig, 1879 (*cf.* Neues Jahrbuch für Mineral., 1880, vol. 2. Referate, p. 342).

[9] Tschermak's mineral. u. petrog. Mittheil., vol. 5, 1883, pp. 157–159.

[10] Bull. U. S. Geol. Survey, No. 28, p. 45.

The common alteration of rock-forming hornblende appears to be to chlorite or to epidote, or into an aggregate of both these minerals. This is almost the only change mentioned by Rosenbusch in his most recent works, although in one place he says: "* * * bei Chloritisirung fasert sich die Hornblende aus * * * " etc.[1] That this change of compact to fibrous hornblende is, however, of great importance, the rocks described in the sequel will abundantly prove.

Chloritization.—An admirable exposition of the present state of our knowledge relative to the so-called "chloritic constituent" of the diabases and allied rocks is to be found in the most recent work of Rosenbusch.[2] The secondary hydrous minerals of a green color, whose almost universal presence has brought to this whole class of rocks the general designation "greenstone," owe their existence to the processes known as weathering, rather than to such as may be strictly called metamorphic. There can be but little doubt that they have been formed mainly out of the components of the pyroxene, although these wander so during the process of the alteration that the new products by no means occupy the exact position of the original mineral. It seems possible to distinguish two classes of such secondary substances: First, such as are more or less fibrous in structure, without pleochroism, and have a decided action upon polarized light; and, second, such as are scaly in structure, with pleochroism and so weakly polarizing as to appear isotropic. The first class embraces substances allied to serpentine; the second, those which more or less closely resemble chlorite. In certain cases they have been chemically identified with such indefinite species as delessite, grengesite (Hisinger), seladonite, chlorophæite (Macculloch), epichlorite (Rammelsberg), diabantachronnyn (Liebe),[3] and diabantite (Hawes).[4] All of these substances resemble each other more or less closely in both physical and chemical behavior, and I am inclined to agree with Rosenbusch[5] in preferring the generic term "*chlorite*" or "*chloritic substance*" for them, to even the indefinite designations "*viridite*" of Vogelsang[6] or "*chloropite*" of von Gümbel. In fact Kenngott has shown that the formula of diabantachronnyn may be brought quite into accord with that of typical chlorite.[7]

Liebe found the greenish coloring-matter of the dark titanic iron diabases of Voigtland and Frankenwald to be picrolite (serpentine), and it is not unusual to observe the curious vermicular aggregates of circular chlorite scales to which Volger has given the name helminth.[8]

It is well known that the results produced by the weathering of horn-

[1] Mikros. Physiog., 2d ed., vol. 2, 1887, pp. 468, 469.
[2] Ibid., pp. 180–184.
[3] Neues Jahrbuch für Mineral., 1870, p. 2.
[4] Am. Jour. Sci., 3d series, vol. 9, 1875, pp. 454–457; Geol. New Hampshire, vol. 3, part 3; 1878, p. 120.
[5] Mikros. Physiog., 2d ed., vol. 2, 1887, p. 183.
[6] Archives Néerlandaises, vol. 7, 1872; Zeitsch. Deutsch. geol. Gesell., vol. 24, 1872, p. 529.
[7] Neues Jahrbuch für Mineral., 1871, p. 51.
[8] Studien zur Entwickelungsgeschichte der Mineralien, 1854, p. 142.

blende or mica are, in most instances, quite similar to those just described in the case of pyroxene. Such a change of hornblende may have an equal importance in those greenstones, like a large proportion of those to be considered in this paper, whose bisilicate constituent was originally augite, but which was subsequently changed by a truly metamorphic process (uralitization) to hornblende before the final weathering commenced.

The last result of the action of the atmospheric influences upon the chlorite is, as Rosenbusch long ago showed, to convert it into an aggregate of limonite, carbonate, and quartz.

Epidotization.—The most careful and detailed observations on this process are to be found in the Inaugural Dissertation of Adolf Schenck on the Diabases of the upper Ruhr Valley and their Contact Phenomena.[1] This investigator finds that certain of these diabases are converted into "Epidosites," or aggregates of epidote and either quartz or calcite. He suggests the only three possible hypotheses for the formation of this epidote, viz: (1) That it was formed by the action of the decomposition products of the bisilicate (mainly CaO and Fe_2O_3) upon the feldspar substance; (2) That the reverse was true, i. e., that the decomposition products of the feldspar (mainly Al_2O_3 and CaO) acted upon the pyroxene; (3) That there was a mutual reaction between the decomposition products of both the original constituents. The first of these hypotheses is regarded by the author as the only tenable one for the rocks which he studied, because in all those diabases which contained much epidote the feldspar was remarkably fresh and the pyroxene decomposed, while in those whose feldspar was extensively altered epidote was almost wanting. Observations of the change of feldspar to epidote are cited from the writings of Dathe, Cohen, Rosenbusch, Liebisch, von Lasaulx, Inostranzeff, Zirkel, Michel-Lévy, Kühn and Scheilitz; and even more authorities are quoted to show that this same mineral originates from augite, or more commonly from hornblende or uralite. If iron is not at hand, the place of the epidote appears to be taken in the feldspar by zoisite. An excellent example of the origin of epidote as a reactionary rim between the substance of hornblende and plagioclase has been described and figured by myself in the Baltimore gabbros and their derivatives. Here the epidote forms a continuous border around the hornblende, its crystals projecting from it outward into the feldspar[2]

Viridite (chlorite)-Epidote Aggregate.—The simultaneous action of the two last described processes (chloritization and epidotization) in an aluminous pyroxene or hornblende results in the production of an aggregate consisting of sharply defined, pale yellow crystals of epidote, imbedded in a green, scaly mass of chlorite. The appearance of this under the microscope is shown on Pl. XI, fig. 1. The magnesia, together

[1] Die Diabase des oberen Ruhrthals und ihre Contacterscheinungen mit dem Lenneschiefer. Bonn, 1884.

[2] Bull. U. S. Geol. Survey, No. 28, 1886, p. 32. Pl. III, Fig. 2.

with a proportion of the iron, alumina and silica, have here formed the chlorite; while the lime, instead of becoming a carbonate, as it often does, has become fixed, in combination with the rest of the iron, alumina and silica, as epidote.

Such aggregates have not escaped the notice of petrographical students, though curious mistakes have sometimes arisen as to their true nature and origin.

In 1874 Dathe described this association of chlorite and epidote with great correctness and precision. He says:

When secondary products become abundant and the leek-green viridite increases in amount and distribution, then there are often associated with this light yellow crystals, whose difference from the viridite is very apparent under the microscope. In the progress of my studies, I have recognized these crystals as pistazite.[1]

In 1876 Zirkel described the change of hornblende to an aggregate of epidote, viridite (chlorite) and magnetite, with which, in many instances, more or less calcite was associated.[2]

In the same year, Wichmann, in his paper on the iron rocks of the south shore of Lake Superior, which was not, however, published until 1880,[3] described this chlorite epidote quite correctly in some instances, although he says that it is beyond doubt that the epidote has been formed out of the viridite. In other cases he regards the mineral imbedded in the viridite as a secondary augite, which, as in the last instance, he thinks was formed from the chlorite. He says of this:[4]

The phenomenon of the transformation of viridite into augite has not been observed until recently. It is very interesting to have the fact established that this mineral, after having been changed into another, has finally returned to its former state. * * * Such individuals are only present in viridite and do not seem to occur in any other part of the rock.

George F. Becker in the course of his microscopical studies of the rocks of the Comstock Lode, Nevada, which were either identical with those investigated by Zirkel, or very closely allied to them, found the same change of bisilicates to an aggregate of chlorite and epidote which the latter observer had recorded. Mr. Becker is, however, very positive that the epidote has been developed after and at the expense of the chlorite, instead of simultaneously with it.[5] This he attempts to explain upon chemical grounds.[6] The improbability of Becker's supposition was brought out by Rosenbusch in a review of his work.[7]

In this, as well as in his more recent text-book,[8] Rosenbusch clearly

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[1] Wenn die Neubildungsproducte sich im Gestein häufen, wenn der lauchgrüne Viridit [Chlorit] an Masse und Verbreitung zunimmt, stellen sich oftmals neben letzteren lichtgelbliche Gebilde ein, deren Verschiedenheit vom Viridit bei mikroskopischer Betrachtung sofort in die Augen springt. Im Verlauf der Untersuchung wurden diese Gebilde als Pistazit erkannt. Mikroskopische Unter suchungen über Diabase. Zeitsch. Deutsch. geol. Gesell., vol. 26, 1874, p. 16.

[2] Microscopical Petrography, Washington, 1876, p. 66, Pl. III, Figs. 2 and 3.

[3] Geol. Wisconsin, vol. 3, 1880, pp. 600–656.

[4] Ibid., pp. 623, 624.

[5] The Geology of the Comstock Lode. Monograph U. S. Geol. Survey, vol. 3, p. 76.

[6] Ibid., pp. 211–214.

[7] Neues Jahrbuch für Mineral., 1884, vol. 2. Referate, p. 189.

[8] Mikros. Physiog., 2d ed., vol. 2, pp. 108, 183.

shows that the true deviation of the chlorite-epidote aggregate is to be found in a division of the bisilicates out of which it is formed, the magnesia passing into the chlorite and the calcium and ferric iron into the epidote. The triclinic feldspar may often materially assist in this formation by furnishing the necessary lime.

Nor is this mistake of Mr. Becker's a new one. Francke in 1875 described the same mineral association and gave the same explanation for it;[1] while in 1880 Schauf,[2] in 1882 Riemann,[3] and in 1884 Schenck corroborated the observation, although both Schauf and Schenck[4] raised unanswerable chemical objections to the derivation of the epidote from the chlorite.

Saussuritization.—The hard, compact, whitish or greenish substance, without luster or cleavage, which forms one of the two main components of the certain coarse gabbros or euphotides, was called by H. B. Saussure, in 1780, "jade."[5] In 1806 Th. Saussure named this mineral, in honor of his father, "saussurite,[6] but its true nature continued for over half a century to elude all mineralogists. As long as chemical analysis was the only means with which it could be studied, any satisfactory solution of the riddle seemed to be impossible. Such investigators as vom Rath,[7] Klaproth,[8] T. Sterry Hunt,[9] and many others obtained the most diverse results; the composition in some cases approaching that of zoisite, in others that of garnet, scapolite, or feldspar. In 1866, Zirkel remarked, at length, upon the extremely imperfect state of knowledge regarding this geologically important mineral.[10]

It remained for the microscope to disclose the composite nature of saussurite as well as to point out the true significance of its origin and occurrence.

Hagge was the first to correctly describe saussurite as an aggregate of colorless or greenish crystal needles, prisms or grains, irregularly scattered through a colorless, glassy-looking matrix.[11] He, however, retained the name saussurite for the included grains, and did not attempt to determine their mineral nature. Hagge also clearly recognized that in all cases observed by him the saussurite was a product of the alteration of feldspar, and that the passage from one mineral to the other was a gradual one which the microscope could easily follow.[12] These results were

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[1] Studien über Corillerengesteine. Inaugural-Dissertation. Leipzig, 1875.

[2] Verhl. d. nat. Vereins d. pr. Rheinl. u. Westf., 1880, p. 6.

[3] Ibid., 1882, p. 256.

[4] Inaugural-Dissertation. Bonn, 1884, p. 45.

[5] Voyages dans les Alpes, vol. 1, Neuchâtel, 1779, p. 83.

[6] Annales de chimie et de physique, 3d series, vol. 16, p. 469.

[7] Poggendorff Annalen, vol. 95, 1855, p. 555.

[8] Beiträge, vol. 4, p. 271.

[9] Am. Jour. Sci., 2d series, vol. 27, 1859, pp. 336–349.

[10] Lehrbuch der Petrographie, vol. 1, p. 27; vol. 2, p. 110, 1866.

[11] Mikroskopische Untersuchungen über Gabbro and verwandte Gesteine. Kiel, 1871. On p. 51 he says: "Der Saussurit besteht aus kleinen Krystallnadeln, Prismen und Körnern, die farblos oder blassgrün sind und regellos in einer wie ein farbloses Glas aussehenden Grundmasse, die auch vielfach klare Spalten in dem Saussurit bildet, verthielt liegen."

[12] Ibid., pp. 35 and 51.

quoted by Zirkel in his text-book, published in 1873.[1] The conclusion that saussurite was "an aggregate and probably the end product of a molecular rearrangement in the feldspar" was also reached by Rosenbusch in the same year.[2] In 1878 Becke showed that the saussurite of certain Grecian rocks was largely zoisite;[3] and in 1883 appeared the important paper by Cathrein upon this subject.[4] This author draws from his work the following six conclusions as to the nature of saussurite.

(1) The so-called saussurite, far from being a homogeneous mineral, is an aggregate of plagioclase, rarely orthoclase, with zoisite. Actinolite, chlorite, and other minerals may also occur as accessories.

(2) The chemical composition of saussurite resembles most that of the lime-soda feldspars; it, however, contains less silica, more lime, and has a higher specific gravity.

(3) The proportions of the saussurite elements can be calculated from the amounts of alkalies, lime, and iron, if we know the species of the original feldspar.

(4) This proportion can also generally be calculated, even when this last factor is unknown, by a consideration of the relative difference of silica, alumina and lime in zoisite and anorthite.

(5) Saussurite is a product of the metamorphism of feldspar through an exchange of silica and alkali for lime, iron and water.

(6) The epidotization of feldspar is genetically the same process as saussuritization and differs only in the larger proportion of iron required.

H. Reusch considered the saussurite which composed a large part of the Bergen gabbros as partly epidote, partly zoisite.[5] Traube found the structure and composition of the saussurite occurring in the gabbros of Lower Silesia to be like that described by Cathrein,[6] while Brögger mentions neither epidote nor zoisite, but regards some member of the scapolite family as probably present in the saussurites studied by him.[7] Paul Michael has recently investigated the saussurite-gabbros of the Fichtelgebirge in Bavaria and concludes that two main types of saussurite occur there. One of these consists mainly of zoisite, with more or less alkaline feldspar, and the other is composed of a pale lime alumina garnet together with serpentine.[8]

J. Lehmann[9] and Lossen[10] were the first to recognize in the saussuritization of feldspar a result of dynamic or regional metamorphism—an idea which Rosenbusch has lately more clearly developed and elabo-

[1] Die mikroskopische Beschaffenheit der Mineralien und Gesteine. Leipzig, 1873, p. 143.

[2] Die petrographisch wichtigen Mineralien, 1873, p. 356.

[3] Tschermak's mineral. u. petrog. Mittheil., vol. 1, 1878, p. 247.

[4] Zeitschr. Kryst., vol. 7, 1883, p. 234.

[5] Die fossilien-führenden krystallinischen Schiefer von Bergen in Norwegen. German translation by Baldauf, 1883, p. 40.

[6] Beiträge zur Kenntniss der Gabbros, Amphibolite und Serpentine des nieder-schlesischen Gebirges. Inaug.-Disser., 1884, pp. 7, 20.

[7] Nyt Mag. for Naturvidenskaberne, vol. 28, 1884, p. 253.

[8] Neues Jahrbuch für Mineral., 1888, vol. 1, pp. 36–41.

[9] Untersuchungen über die Entstehung der altkrystallinischen Schiefergesteine, etc. Bonn, 1884, pp. 197, 199.

[10] Jahrbuch k. preuss. geol. Landesanstalt für——p.——

rated.[1] This last-named authority shows that the new mineral developed in the feldspar is by no means always of necessity zoisite or epidote. It may also be garnet, or a mineral of the scapolite family. He remarks:[2]

The sum total of these new products, which are certainly not produced by normal weathering, but are due to a metamorphic process, we designate as the *saussuritization* of feldspar.[3]

Michel-Lévy was the first to show that the so-called "spotted-gabbro (gefleckter Gabbro) of Brögger and Reusch was a mixture of amphibole and wernerite;[4] and Sjögren has since demonstrated that the latter mineral is secondary to feldspar, and the first to pyroxene. Fouqué and Michel-Lévy tried the interesting experiment of fusing this rock, and obtained therefrom an aggregate of pyroxene and labradorite.[6]

Formation of the Albite Mosaic.—Analogous and closely related to the saussuritization of feldspar are cases where, in the process of its alteration by metamorphism, the lime is more or less completely removed or crystallized as calcite, instead of forming a calcium silicate. In such instances the alkaline portion of the plagioclase molecule crystallizes in the form of a finely granular aggregate, or mosaic of limpid grains (albite). These may be wholly devoid of twinning lamellæ and often closely resemble quartz, with which they are not infrequently associated. Of course such mosaics are connected by every stage of transition with saussurite, according as more or less of the lime has remained as a calcium silicate (zoisite or epidote).

Such a granulation of the feldspar substance has already been alluded to under the head of microstructural metamorphism; but, inasmuch as a complete solution and recrystallization of clear feldspar substance often takes place, it belongs quite as much to this division of the subject. The geological significance of this method of feldspar alteration, especially in certain basic eruptive rocks like diabase, has been most persistently emphasized by Lossen. He has shown how it may result in the total obliteration of the original and characteristic rock-structure, and how, therefore, it may prove most misleading, unless its nature and origin are clearly understood.[7] J. Lehmann,[9] Teall,[8] and others have also observed and commented on such a secondary feldspar mosaic.

Sericitization.—The soft, unctuous mineral characteristic of so many slates and schists was formerly regarded as talc. This gave rise to the

[1] Mikros. Physiog., 2d ed., vol. 2, 1886, p. 164.

[2] Ibid., p. 137.

[3] "Die Gesammtheit dieser Neubildungen, die sicher keine Art der normaler Verwitterung, sondern ein metamorpher Vorgang ist, bezeichnet man als die *Saussuritisirung* des Feldspaths."

[4] Bull. Soc. Minéral. de France, vol. 1, 1878, pp. 43, 79.

[5] Geol. Föreningens Stockholm Förhandl., vol. 6, 1883, p. 447 (Neues Jahrbuch für Mineral., 1884, vol. 1, referate p. 81).

[6] Bull. Soc. Minéral. de France, vol 2, 1879, p. 105.

[7] Jahrbuch preuss. geol. Landesanstalt für 1883, p. 640 Pl. 29; ibid., 1884, pp. 525–530, Pl. XXIX, Figs. 2 and 4.

[8] Untersuchungen über die Entstehung der altkrystallinischen Schiefergesteine, etc., 1884, p. 207.

[9] Quart. Jour. Geol. Soc. London, vol. 41, 1885, p. 139.

common designation "soapstone" or "talcose slates," which was used very early in America by Amos Eaton.[1] As early as 1819, however, Prof. Chester Dewey, of Williams College, made the statement that he was able to detect very little magnesia in the specimens which he examined, while alumina was abundant. He therefore preferred to call these rocks micaceous slates.[2]

In Europe, slates of this kind were first studied from the Taunus, where they were usually regarded as talcose until 1847, when Sandberger made the same discovery that Dewey had made with regard to the American rocks.[3] List subsequently studied more carefully this micaceous constituent of the Taunus schists, and named it, on account of its silky luster, "Sericite."[4] Scharff attacked the conclusions of List and considered sericite to be only a mixture,[5] while Lossen vigorously defended the individuality of the mineral.[6]

The sericite was soon identified by many investigators in the rocks of many regions.[7] Prof. Dana united it with the species margarodite and damourite in the group of hydro-micas and called this class of slates the hydro-mica slates. Of these so-called hydro-micas Prof. Dana says:

> The following species [margarodite, damourite, parophite, sericite, sericite schist, groppite, euphyllite, cookeite, voigtite, roscoelite,] are mica-like in cleavage and aspect, but talc-like in wanting elasticity, in greasy feel, and in pearly luster. They are sometimes brittle. Common mica, muscovite, readily becomes hydrated on exposure; but hydrous micas are not all a result of alteration. Hydro-mica schists form extensive rock-formations, equal to those of the ordinary mica-schists.[8]

In 1880 Laspeyres made a very thorough examination of sericite and showed conclusively its identity with muscovite.[9] It differs from the ordinary form of this species only in its compact structure and in its geological significance; but, since both of these are characteristics, there is a decided advantage in retaining the name sericite, especially in petrography, to designate a peculiar form and occurrence of muscovite.

The alteration of orthoclase into kaolin or clay was very early known.[10] The corresponding change of the same feldspar into mica was first observed by Haidinger in 1841,[11] but was subsequently found to be not

[1] Index to the Geology of the Northern States, pp. 147, 174, 286.

[2] Am. Jour. Sci. 1st series, vol. 1, 1819, p. 340. Thus the discovery, usually attributed to Sandberger, was anticipated in America by twenty-eight years. Cf. Dana's Manual of Geology, 3d ed., p. 72.

[3] Uebersicht d. geol. Verhältnisse d. Herzogth. Nassau, 1847, p. 94.

[4] Jahrb. d. Vereins f. Naturkunde im Herzogth. Nassau, vol. 6, 1850, p. 126; vol. 7, 1851, p. 266; vol. 8, 1852, p. 128; Annalen Chem. und Pharm., vol. 81, 1852, p. 181.

[5] Neues Jahrbuch für Mineral., 1868, p. 309; ibid., 1874, p. 271.

[6] Zeitschr. Deutsch. mineral. geol. Gessell., vol. 19, 1867, p. 509; vol. 21, 1869, p. 281.

[7] e. g., by Pichler in the Tyrol. Neues Jahrbuch für Mineral., 1871, p. 56; by Törnebohm in Sweden, Neues Jahrbuch für Mineral., 1874, p. 141; by von Lasaulx in the Ardennes; by Credner in Saxony and by Wichmann in the Lake Superior rocks.

[8] Manual of Mineralogy and Petrography. 4th ed. New York, 1887, p. 335.

[9] Zeitschr. Kryst., vol. 4, 1880, pp. 244–256.

[10] Blum: Pseudomorphosen d. Mineralreiches, 1843, p. 72.

[11] Abh. d. k. böhm. Gesell. d. Wissenschaft, 1841, p. 4. Blum: Pseudomorphosen, Nachtr., I, 1847, p. 25.

uncommon. Since rocks have been studied with the microscope, the change of potash feldspar to muscovite or sericite has been found to possess a wide significance, especially in dynamic metamorphism.

There seems every reason to believe that sericite always originates from potash feldspar and not from other micas. Its constant and very intimate association with quartz shows, as first pointed out by Laspeyres,[1] that it was derived from an acid silicate.

Any rocks, therefore, whether sedimentary or massive, which contain orthoclase, may give rise to sericite; but its formation, in any case would seem to require the action of some great dynamic force. The close relation between dislocation and mica formation, so clearly illus, trated by J. Lehmann,[2] is in an eminent degree applicable to sericite. It is now a well known and oft-recorded fact that in any rock mass, where the strains and stresses have been the most intense, there the micaceous minerals are most abundant; and if the rocks are orthoclastic these will be largely sericite. Sericitization is therefore a phenomenon of dynamic metamorphism. It is in a way, as Lehmann says, a retrogressive metamorphic process, since feldspar is by it not formed, but destroyed. It is also the most extreme manifestation of dynamic action in orthoclase rocks and may produce the same result—a sericite schist—from a clastic arkose on the one hand, and from a massive granite or quartz-porphyry on the other.[3]

In an admirable paper on the paragenesis of certain ore deposits, A. von Groddeck has shown that the rocks, heretofore considered as talcose, which occur near Holzappel and Werlau on the Rhine, at Mitterberg in Salzburg and at Agordo in the Venetian Alps, are in reality sericite schists. These he considers to represent the extreme phase of metamorphism, in some cases of an eruptive rock (diabase), and in other cases of a normal clay state or graywacke.[4] It seems most probable that these rocks owe their origin to dynamic agencies, with which the deposition of the ore also stands in close relationship.

The alteration of the feldspathic groundmass of quartz porphyries to muscovite or sericite, especially where these have been rendered schistose by pressure, is now well known. In this way porphyroids may be derived from massive eruptive rocks. In the more massive quartz porphyries studied by C. Schmidt from the central Alps (Windgällen), sericite is met with as an occasional pseudomorph after the feldspar, but in the schistose porphyries derived from the latter by pressure and stretching, this mineral is much more abundant; so abundant, indeed, as, in some instances, to make up, along with quartz, the whole mass of the rock.[5]

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[1] Zeitschr. Kryst., vol. 4, 1880, p. —.

[2] Untersuchungen über die Entstehung der altkrystallinischen Schiefergesteine. Bonn, 1884. Cap. IX. Druckschieferung und Glimmerbildung, p. 136.

[3] Ibid., p. 101.

[4] Zur Kenntniss einiger Sericitgesteine, welche neben und in Erzlagerstätten auftreten. Neues Jahrbuch für Mineral., Beilage-Band 2, 1883, pp. 72–138.

[5] Neues Jahrbuch für Mineral., Beilage-Band 4, 1886, p. 428.

Alterations of titanic iron.—The element titanium exists in unaltered diabases almost exclusively in combination with iron as ilmenite or as titaniferous magnetite. In the processes of metamorphism, however, various other titanium compounds are formed. The most common phase of this change consists in the development of a gray rim around the the ilmenite grains. This substance is also often seen along the rhombohedral cleavage cracks of the ilmenite, giving rise to the well known gridiron structure so often figured.[1] There can be no doubt that this gray material is an alteration product of the ilmenite, although Gümbel, who gave it its name, *leucoxene*, regarded it as a parallel growth of another mineral.[2] Much difference of opinion formerly prevailed in regard to the chemical nature of the leucoxene. Zirkel at first regarded it as iron carbonate,[3] Cohen as titanic oxide,[4] Rosenbusch as anatase.[5] Gümbel regarded it as probably a titanosilicate, while both Fouqué[6] and Michel-Lévy[7] thought that it was a form of sphene. The identity of both leucoxene and titano-morphite (another similar substance described by von Lasaulx around the rutile of an amphibolite from Lampersdorf in Silesia)[8] with titanite or sphene was first conclusively proved by A. Cathrein in 1882.[9]

The frequent passage of the dull gray leucoxene rim into clearly defined aggregates and crystals of sphene is mentioned by Cathrein,[10] and the origin of sphene by the alteration of ilmenite is also described by W. C. Brögger.[11] Fine examples of this origin for sphene are also described and figured in the sequel.

Anatase has been described as an alteration product of ilmenite, by Diller.[12]

The rutile needles frequently seen about ilmenite, either with or without leucoxene, are regarded by Cathrein as an original intergrowth of this mineral with the ilmenite.[13] Further reference will be made hereafter to needles of this character occurring in some of the Menominee greenstones.

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1 Cf. Vallée de la Poussin et Renard: Roches plutoniennes de la Belgique, etc., 1874, Pl. VI, Figs 31 and 32.

2 Palæolithische Eruptivgesteine des Fichtelgebriges, Munich, 1874, p. 35.

3 Mikroskopische Beschaffenheit d. Min. u. Gest., 1873, p. 409.

4 Erläuternde Bemerkungen z. d. Routenkarte, etc., 1875, p. 55.

5 Mikros. Physiog., 1st ed., vol. 2, 1877, p. 336.

6 Cours de Collège de France, 1877.

7 Bull. Soc. Géol. France, 3d series, vol. 6, 1878, p. 163.

8 Neues Jahrbuch für Mineral., 1879, p. 568.

9 Zeitschr. Kryst. u. Min., vol. 6, 1882, p. 244.

10 Ibid.

11 Nyt Mag. for Naturvidenskaberne, vol. 27, 1881, p. 359.

12 Neues Jahrbuch für Mineral, 1883, vol. 1, p. 193.

13 Zeitschr. Kryst. u. Min., vol. 6, p. 256.

CHAPTER II.

GREENSTONE BELTS OF THE MENOMINEE IRON DISTRICT.

INTRODUCTORY AND HISTORICAL.

The exact geographical position of the two greenstone-schist areas of the Menominee region are fully indicated in the explanatory and historical note by Prof. Irving at the beginning of this memoir and upon the accompanying geological map of this district. (Pl. II). The same note explains and discusses the different views which have been held by various geologists in regard to the stratigraphical position of these greenstone schists in the general succession of the stratiform rocks of the Menominee region.

A brief mention of the opinions which have already been published regarding the petrographical character of these greenstone schists is, however, desirable.

The first attempt to describe the Menominee greenstones and greenstone schists lithologically was made by Hermann Credner in 1869, from observations collected while he was acting as assistant to Prof. Pumpelly on a survey for the Portage Lake and Lake Superior Ship Canal, during the years 1867–'68.[1] In his first paper entitled *Die vorsilurischen Gebilde der oberen Halbinsel von Michigan in Nord-Amerika*,[2] Credner gives a section of the strata of the Menominee Iron Region, commencing with the oldest member, from which the following is abbreviated:

	Feet.
a. Quartzite	8,000
b. Crystalline dolomitic limestone	3,500
c. Red Iron ore	600–1,000
d. Chlorite schist	1,000–1,500
e. Clay slate	8,500
f. Chlorite schist with diorite	1,200–1,400
g, h, i, k. Talc schist	150
l. Dioritic series	2,300
m. Talcose clay slate	1,500

The members *f* and *l* are evidently parts of the same formation, in which the beds *g*, *h*, *i*, and *k* are interstratified. In his description of *f*, Credner says:

In the upper horizon of this series there occur beds of fine and coarse grained diorite and aphanite, varying in thickness from ten feet to several hundred. These

[1] See Geology of Michigan, vol. 1, 1873, p. 157, note.
[2] Zeitschr. Deutsch. geol. Gesell., vol. 21, 1869, pp. 516–554.

rocks consist mainly of dark green hornblende and white or pale green oligoclase, with which granular or scaly chlorite is often associated. Crystals of pyrite and magnetite are also frequent. Indications of a lamellar parting are frequent, while rectangular jointing is rare.[1]

In the same article, in speaking of the member *l*, the author says:[2]

Dioritic series 2,300 feet in thickness. Mainly a fine grained or aphanitic, rarely a coarsely crystalline aggregate of the constituents of diorite. All contain crystals of pyrite; the aphanite contains veins of calcite and quartz.[3]

In a second article entitled *Ueber nordamerikanische Schieferporphyroide*, which also deals with certain rocks exposed on the Menominee River,[4] Credner unites his beds *f* and *l* as "chlorite schist alternating with intercalated diabase;" while his *g*, *h*, *i*, and *k* are described as a series of "porphyroid-schists," 300 feet in thickness, between two beds of diabase.

In the year 1869 the geological survey of Michigan was inaugurated with the iron-bearing formations of the Upper Peninsula, in charge of Maj. T. B. Brooks. The results of his labors appeared in 1873,[5] accompanied by two appendices, containing special petrographical descriptions of the rocks collected by Julien,[6] and Wright.[7] Several of the Menominee greenstones, both massive and schistose, come within these descriptions, but the descriptions are for the most part vague; as, for instance "diorite," "dioritic schist," "porphyritic diorite," etc.

In 1874 Major Brooks continued his studies of the Menominee region under the auspices of the Wisconsin Geological Survey. The results of this work appeared in 1879[8] and contained much more elaborate and accurate determinations of the greenstones and greenstone schists. Major Brooks gives a diagram[9] to illustrate his general views of the observed transitions of greenstones (believed to be mostly metamorphosed sediments) into related rocks. Dr. Wichmann, who furnished the systematic petrographical descriptions of these rocks in Brooks's report,[10] however, regarded these rocks as for the most part eruptive and to a large extent as derived from diabase. Special reference will be made to the descriptions of Wichmann and others who have worked

[1] Zeitschr. Deutsch. geol. Gesell., vol. 21, 1869, p. 528.

[2] Im oberen Horizonte dieser Schichtenreihe treten von 10 bis mehrere hundert Fuss mächtige Einlagerungen von fein- bis grobkörnigem Diorit sowie von Aphanit auf. Sie bestehen vorwaltend aus dunkelgrüner Hornblende und weissem oder hellgrünem Oligoklas, wozu sich an manchen Punkten viel körnig-schuppiger Chlorit gesellt. Einsprenglinge von Schwefelkies und Magneteisenstein sind in ihnen häufig. Andeutung von plattenförmiger Absonderung ist gewöhnlich, quarderförmige Absonderung selten.

[3] Ibid., p. 529.

[4] Dioritische Gesteinsreihe von 2,300′ Mächtigkeit. Vorwaltend ein feinkörniges oder aphanitisches, seltener ein grobkrystallinisches Gemenge der Bestandtheile des Diorites, alle mit Schwefelkies ein ein sprenglingen, die Aphanite mit Schnüren von Kalkspath und Quarz.

[5] Neues Jahrbuch für Mineral., 1870, pp. 970–984.

[6] Geol. Survey Michigan, vol. 1, Upper Peninsula. Part I. Iron-bearing rock, by T. B. Brooks. 1873.

[7] Ibid., vol. 2, 1873. Appendix A, Lithological descriptions, etc., of 259 specimens of the Huronian and Laurentian of the Upper Peninsula, by A. A. Julien, pp. 1–197.

[8] Ibid., vol. 2, 1873. Appendix C. Microscopic determinations and descriptions of 78 specimens of Huronian rocks and ores, by C. E. Wright, pp. 213–231.

[9] Geol. Wisconsin, Vol. 3, 1873–1879. The Geology of the Menominee Iron Region, Oconto County, by T. B. Brooks, pp. 429–663. Ibid., Geol. Menominee Region by C. E. Wright, pp. 665–741.

[10] Ibid., 519.

[11] Ibid., pp. 600–656.

upon the petrography of the Menominee greenstones in the course of the following chapters of this work.

All observers seem to be agreed that the association of the massive greenstones with those which are more or less perfectly schistose is an extremely intimate one. Even Major Brooks, in spite of his idea that most of the greenstones are altered sediments, is constantly suggesting the possibility of a mechanical origin for the intercalated schistose layers. He says[1] of the Twin Falls exposure:

> This slaty material may be simply a compacted form of the pulverized greenstone produced at the time of fissuring.

Again,[2] in speaking of the Commonwealth and Eagle Mine rocks:

> It will be observed that these rocks have some resemblance to *aa*, but it is believed that they are associated schistose and altered varieties of the great greenstone bed XVIII, so extensively developed to the north and east.

He says[3] also:

> An unevenly splitting, gray-green schist associated with greenstones and apparently derived from them by alteration of the amphibole, is included in this family [chlorite schist], although its origin and associations are widely different from the above.

Again:[4]

> One of the largest, most generally distributed, and at the same time, obscure varieties embraces those chloritic rocks that are associated with greenstones.

Dr. C. Rominger, in his Report on the Geology of the Menominee Iron Region,[5] is equally impressed with the close association of the massive and schistose varieties of the greenstones. Like Brooks, he regards them as of sedimentary origin, and thinks that the massive portions are the result of extreme metamorphism, having recrystallized from a partially fused state.

There seem to be only three different ways of explaining the facts as they are plainly and abundantly manifested at each of the several points examined on the Menominee River.

We may suppose, as did Foster and Whitney, Whittlesey and Credner, that the schistose portions of the rocks exposed at these several points are more or less perfectly metamorphosed sedimentary material, while the more massive portions represent intercalated beds of eruptive origin.

We may imagine, on the other hand, as did Rominger and Brooks, that all of these rocks, including the most schistose and the most massive phases, are probably altered sedimentaries; supposing, with Rominger, that the more massive kinds are merely the same sedimentary material fused by the intensity of the metamorphosing action so as to lose all trace of the original stratification; or admitting, with Brooks, the possibility, though great improbability, that some of the more massive phases like the gabbro of Sturgeon Falls, are of eruptive origin.

[1] Geol. Wisconsin, vol. 3, 1873-1879. The Geology of the Menominee Iron Region, Ocorets County, by T. B. Brooks, p. 477.
[2] Ibid., p. 484.
[3] Ibid., p. 516.
[4] Ibid., p. 518.
[5] Geol. Michigan, vol. 4, 1881, p. 209.

Finally, we may imagine that all phases seen at these several places represent material of eruptive origin whose stratiform structure is due to secondary dynamic agencies. This last view has heretofore been advanced only by Irving, who, however, has presented it very briefly, and without descriptions or petrographic proof.[1]

It is the aim of the present portion of this paper to set forth all the evidence that a careful examination of these rocks can furnish as to which of these three views best explains their true origin and mutual relations. This material will first be presented in the form of a detailed description of each of the five localities selected for this purpose on the Menominee River (see Pl. II). The general results thus secured will be summarized, in connection with those obtained elsewhere, in Chap. VI. The Menominee localities will be treated of in regular order, commencing with the one farthest down the river, Sturgeon Falls.

STURGEON FALLS.

Kinds of rock.—This exposure is situated a short distance below the mouth of the Sturgeon River, in Sec. 27, T. 39 N., R. 29 W., Michigan. Its general topography may be seen from the accompanying map (Pl. III), which is copied from Pl. I, in Major Brooks's report with double his linear scale. Only the rocks exposed on the eastern or Michigan side of the river were examined; but those opposite could be seen to be of the same character.

The barrier which here forms the falls consists of two belts of massive rock, *f* and *h*, between which are softer schists, *g*. These are also intercepted by a harder and more massive band.

The massive rock is light in color and of a comparatively coarse grain. It is quite elaborately described in Major Brooks's report,[2] and designated on the authority of Wapler, Rutley, and Pumpelly as a gabbro. Julien also examined this rock, but seems to have mistaken the diallage for hornblende, and the brown pleochroic hornblende for biotite. Rutley's opinion is given with hesitation. Pumpelly's description is brief and accurate. He says:[3]

> Saussurite-gabbro (or hornblende gabbro): contains saussurite, diallage, hornblende. Identical under the microscope with the coarser crystalline rock of Upper Quinnesec Falls.

This rock was considered serpentine by Foster and Whitney[4] and was provisionally named "porphyritic, speckled diorite" by Brooks, who separated it as his Bed XV of the Huronian.

The massive occurrence at *f* is represented by Nos. 11154, 11155, and 11162; that at *h* by Nos. 11167, 11168, 11169, and 11170. Nos. 11156–11161, and 11163–11166 were collected from the softer schistose bands at *g*.

These rocks are particularly noteworthy as being the only ones discovered on the Menominee River which contained any trace of pyroxene.

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[1] Fifth Annual Report U. S. Geol. Survey, p. 190. [2] Geol. Wisconsin, vol. 3, pp. 455–563. Ibid[3]., p. 564. [4] Report on the Geol. Lake Superior Land District Plate 2, p. 25.

We shall find that they agree perfectly with Pumpelly's description above cited, the hornblende being in part secondary, and they are hence to be designated as saussurite-gabbro. The least altered specimens were found at *h* (Nos. 11167–11170). The rock at *f*, although essentially the same as at *h*, is more changed and somewhat schistose along certain bands, while some of the specimens found at *g* were clearly once the same as the others, but now represent a third and much more advanced stage of alteration. I shall first describe these three stages of the undoubted gabbro, and then trace their relation to the intermediate schists.

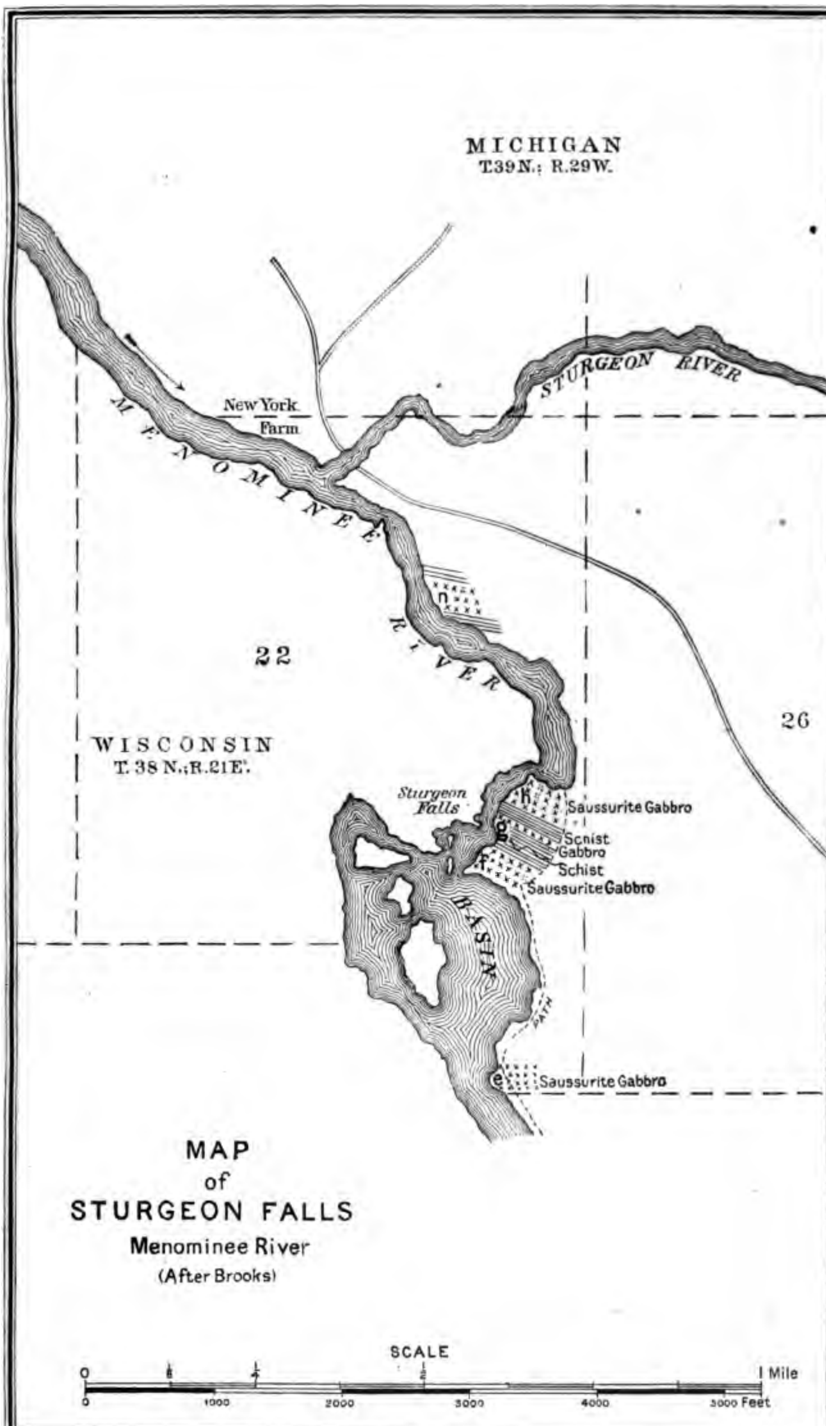
Saussurite-gabbro (*first stage*).—The color of this rock in the hand specimen is rather light. On a fresh fracture it shows a finely mottled structure of white and dark greenish-gray. Examined with a pocket-lens, the mottling is seen to be due to two minerals. One of these is opaque white, sometimes tinged with green, and only rarely exhibits the glistening cleavage surface of feldspar. The darker mineral has a brownish color and almost a metallic luster on its cleavage surface. It is, however, always tinged with green on account of incipient alteration.

No other constituents are microscopically visible. The structure of the rock is irregularly granular. The grain is as a rule moderately fine but is subject to sudden local variation which develops comparatively coarse-grained patches in the main mass.

Of this freshest type of the gabbro four thin sections were studied, viz, 11167, 11167[a], 11168 and 11170. All show profound alteration in the original constituents, due to dynamic processes. These are, however, most intense in No. 11167, which has been subjected to such great pressure as to present a transition form to the second stage of this gabbro. Nos. 11167[a], 11168, and 11170, are practically identical and may be described together.

Under the microscope this rock is seen to be composed of plagioclase, almost wholly altered to a gray and opaque saussurite; diallage, of a very light gray color; hornblende, partly original, partly secondary, and a little titanic iron (ilmenite). Certain alteration products, like quartz, calcite, and a colorless chlorite, are also present in varying quantity.

The feldspar has no crystal form of its own (i. e., it is allotriomorphous, in the sense of Rosenbusch). It seems to have crystallized simultaneously with the diallage, or if anything later. It is hardly ever so unaltered as to present its original twinning-lamellæ, but when this is the case the high extinction angles and brilliant interference colors observed indicate a basic feldspar. No further determinations could be made on this mineral because of its almost complete alteration to a dull opaque white saussurite. Even in the thinnest sections this substance remains opaque for the lower powers of the microscope, being composed of such fine grains that it must be highly magnified before it can be resolved. Under higher powers, however, it is seen to be made



MAP
of
STURGEON FALLS
Menominee River
(After Brooks)

up of small zoisite grains, embedded in a clearer matrix, which is probably albite.[1]

This saussurite substance is traversed in all directions by lighter—sometimes quite clear and transparent—veins, which are composed largely of secondary albite. This in at least one instance (No. 11168) shows the characteristic twinning striation of plagioclase (see Fig. 4). In other cases, however, these veins appear to be composed of quartz or chlorite (see Pl. VIII, fig. 1).

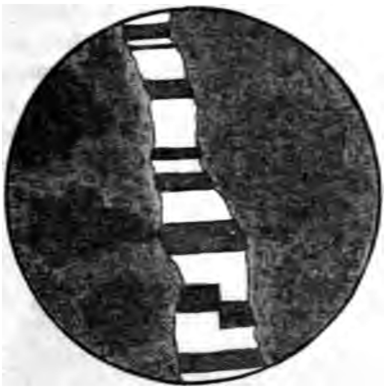


FIG. 4.—Veins filled with secondary albite in the altered gabbro of Sturgeon Falls (No. 11168). Represented in polarized light in order to show the twinning striæ. Magnified 350 diameters.

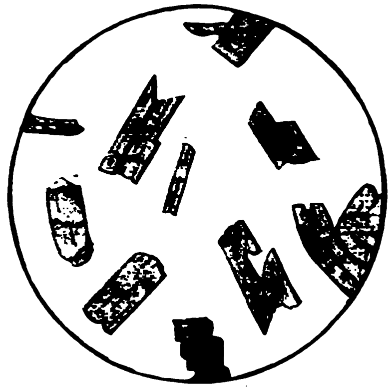


FIG. 5.—Zoisite crystals in a coarse saussurite from the altered gabbro of Sturgeon Falls. Magnified 180 diameters.

In certain cases, notably in section No. 11167, the saussurite aggregate is coarser and the zoisite plainly visible and easily determinable. Fig. 5 shows characteristic forms of this mineral. Its crystals are always without terminal planes, but they have a perfectly developed cleavage parallel to their vertical axis and a cross-jointing. Between crossed nicols they are seen to be twinned, sometimes polysynthetically, like albite. The zoisite is itself colorless, with a high index of refraction, but a weak double refraction; the interference colors are therefore dull, either gray or bluish, and sometimes a deep ultramarine. The extinction is parallel to the cleavage lines.

One unusually large crystal of zoisite, represented in Fig. 6, exhibits all of these characteristics, and also, when examined in converged polarized light, it gives a biaxial interference figure with the plane of the optic axes perpendicular to the cleavage. (Fig. 6.)

[1] Zeitschr. Kryst. u. Min., vol. 7, pp. 234–249. Cathrein, in this article, calculates a number of saussurite analyses to show the relative amounts of feldspar and zoisite or epidote present. He seems to think that the feldspar left after subtracting the zoisite gives the original constitution of the mineral before its change to saussurite, and attributes the alteration to the addition of CaO and Al_2O_3 and loss of silica and alkalies (p. 243). Another hypothesis would be that the original feldspar was much more basic (i. e., contained more CaO, Al_2O_3 and less SiO_2 and Na_2O) than the one now forming the matrix of the saussurite, and that this compound broke up without material chemical change into two compounds, one a more acid plagioclase, like albite or oligoclase and the other zoisite, which would contain what CaO and superfluous Al_2O_3 was left after the change. A similar separation of one mineral into two has been traced by Profs. J. Brush and E. S. Dana in the alteration of spodumene into a minute aggregate of eucryptite and albite. (Am. Jour. Sci., 3d series, vol. 20, p. 257 et seq., 1880.)

The diallage of these rocks is quite colorless when seen in a thin section, although in the form of powder it is a light grayish green. The prismatic cleavage is well developed, but not as much so as the very perfect parting parallel to the orthopinacoid, which is the characteristic feature of diallage (Pl. VIII, fig. 1). The extinction angle was found to be as great as 35° in the prismatic zone. The plane of the optic axes is perpendicular to the orthopinacoidal parting, and a single axis appears in such sections as show a prismatic angle of nearly 90°. This diallage is very sensitive to the action of pressure and is frequently much bent and twisted. The mineral is sometimes separated along cleavage cracks, the interstices being filled with a colorless, isotropic alteration product, which is probably some variety of chlorite. This substance becomes much more abundant in the more altered forms of this rock and will be again mentioned. The diallage is also often traversed by veins filled with clear quartz.

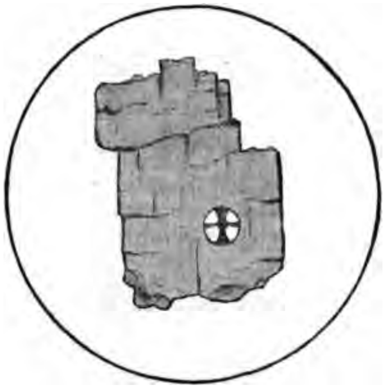


FIG. 6.—Large crystal of zoisite in saussurite of No. 11167. Altered gabbro from Sturgeon Falls. Magnified 350 diameters.

FIG. 7.—Border of both compact and fibrous hornblende around diallage in the Sturgeon Falls gabbro (No. 1167a). Magnified 180 diameters.

The hornblende is an important and constant constituent of the Sturgeon Falls gabbro. It is for the most part compact, and brown in color, having the usual pleochroism. More rarely it is green, or apparently bleached to a lighter shade of brown. In a few instances this latter process has been carried so far as to make it quite colorless. The hornblende is in all cases most intimately associated with the diallage. At times it forms a continuous border of varying width around the diallage crystal, and in other instances it penetrates the latter mineral in irregular areas (see Pl. VIII. fig. 1). In some cases a delicate fringe of minute, colorless hornblende fibers is seen to lie on the outer side of the compact hornblende border and penetrate the saussurite substance (see Fig. 7). This is the same phenomenon that has recently been described by Lossen.[1]

[1] Studien an metamorphischen Eruptiv- und Sedimentgesteine, etc., cf. Jahrbuch preuss. geol. Landesanstalt für, 1884, p. 543, Pl. XXIX, fig. 2. (Cf. Van Hise: Am. Jour. Sci., 3d series, vol. 33, 1887, pp. 385 et seq.

It is impossible to say with certainty what the origin of the compact brown hornblende is. It may be an original product of crystallization in the magma, but its mode of occurrence and its general character indicate that it is probably of secondary origin, having originated by paramorphism of the diallage, as has been shown by myself[1] and by Lossen[2] to be sometimes the case.

No other constituents are important in this rock. Iron in any form seems to be quite rare in it. Occasional cloudy grains, resembling leucoxene, may represent some original ilmenite, while minute crystals of pyrite are still rarer.

The structure of the rock seems to be irregularly granular; none of the components being in any degree idiomorphic. Frequent and abrupt changes in the coarseness of the grain are observable.

All specimens show the action of dynamic forces which have more or less profoundly affected the different constituents. These effects are particularly noticeable in slide No. 11167. Here the rock seems in places to have been crushed and a mosaic of the component minerals to have been formed. Hornblende, generally colorless, is unusually abundant. Colorless chlorite and zoisite are also developed, and all are mixed indiscriminately. In one part of the section a vein is seen to traverse the rock. This is filled with limpid quartz in long, wedge-shaped areas, which extend from one side of the small fissure to the other. This quartz is traversed by long, colorless fibers of the greatest delicacy, and it also contains a good deal of the colorless chlorite, both in solid masses and in those peculiar vermicular groups to which Volger has given the name helminth. These curious groups, which resemble piles of little coins, are sometimes straight, sometimes curved. They are so minute as to be visible only with a high magnifying power. Fig. 8 represents them as they appear when magnified 350 diameters. Exactly the same mineral has been described in the secondary quartz of diabase by Möhl,[3] von Lasaulx,[4] and Schenck;[5] and in that of schalstein and syenite by Hussak.[6]

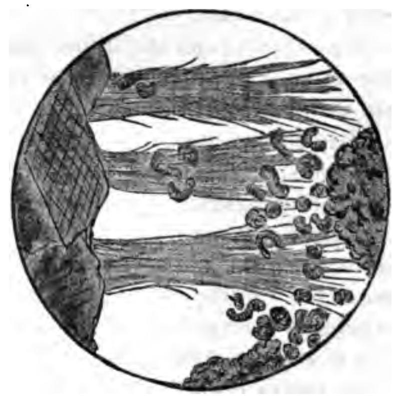


FIG. 8.—Vermicular chlorite (helminth) in quartz. Vein in altered gabbro, Sturgeon Falls.

Saussurite gabbro (second stage).—Representatives of this type are found at the lower end of the falls, at *f* on Major Brooks's map, and

[1] Am. Jour. Sci. 3d series, vol. 28, Oct., 1884, p. 262.
[2] cf. Jahrbuch preuss. geol. Landesanstalt für 1883, p. 632.
[3] Neues Jahrbuch für Mineral., 1875, p. 716.
[4] Verh. d. naturh. Vereins d. preuss Rheinl. u. Westf., 1878, p. 216.
[5] Inaugural-Dissertation. Bonn, 1884, p. 22.
[6] Tschermak's mineral. u. petrog. Mittheil., vol. 1, 1878, p. 275.

at his *e*, at the lower end of the basin below the falls. Nos. 11153 and 11154, from these two localities, are identical in mineral composition with the rocks of the first type above described. They are of a dirty greenish gray color and indications of a schistose structure have already begun to appear in them. Under the microscope they disclose the same constituent minerals as the rocks of the first type; nor are these minerals much more altered, but they show the effects of a profound mechanical action. The feldspar is remarkably fresh and its twinning lamellæ are quite distinct, but it is everywhere crushed, broken, and faulted. The crystals are often plainly seen to be separated into a number of fragments which are removed a considerable distance from one another. Frequently a fine grained mosaic has been formed by the crushing of the larger feldspar crystals. In other cases (especially in section 11154) the feldspar is not so much broken, but it is altered around its edge to an opaque, gray saussuritic mass, while its interior is hardly changed. (See Pl. VIII, fig. 2). The diallage is more altered than in the rocks last described, although it can still be seen to belong to the same species. The crystals are very much bent and twisted and frequently so changed to the light-colored chlorite that only a few minute remnants of the brightly polarizing mineral remain in this nearly isotropic base. (See Pl. VIII, fig. 2.) Fibrous hornblende now becomes more abundant than the compact, and leucoxene patches are seen at intervals.

Nos. 11162, from the upper part of the point *f*, and 11172 from above the falls at *n*, present interesting varieties of this rock. They do not show the effects of crushing to such a degree as do those just described. Indeed the original structure of the rock seems well preserved, although the feldspar is almost completely changed to a fine grained, nearly opaque saussurite, and every trace of the pyroxene (diallage) has disappeared. A pale green, fibrous hornblende occupies the place of this mineral, and there seems to be every reason for regarding it as derived from the diallage; although in No. 11172 the abundant remains of a compact, brown hornblende, evidently in the process of changing to the fibrous modification, suggests the possibility of this mineral having been the original bisilicate constituent. Still there is no warrant for assuming that what is essentially a diallage rockmass was locally developed as a hornblendic rock; and it may be that this is an instance of a remarkable *passage of a pyroxene through a compact into a fibrous hornblende*, for which we shall find much evidence in the studies that follow.

Saussurite gabbro (third stage).—As has been already remarked and as may be seen on the map of Sturgeon Falls (Pl. III), there is, between the two points of the more massive rock, *h* and *f*, an area *g*, composed of softer schists. These are easily eroded and have thus occasioned the small bay. The passage from the fresh and massive gabbro at *h* into

these schists seems to be a gradual one. Along the lower side of *h* there are rocks which are without doubt essentially the same as those above described from this point but which have been profoundly altered by dynamic action, which has also occasioned considerable chemical changes. These rocks, while they show remains ot their original minerals, have become decidedly schistose; and by the alteration in their composition, they have developed certain other points of similarity with the schists at *g*, into which they appear gradually to pass. For this reason they have been selected to represent the third and most altered stage of the gabbro in which any sure signs of the original character of the rock still remain; at the same time they possess even more of the characters belonging to the schists, and thus afford just the evidence desired that the latter are the extremely modified form of the massive rock.

No. 11166 is only indistinctly schistose, showing a soft grayish green matrix in which are imbedded altered grains of a reddish feldspar. Under the microscope the original coarsely granular structure of the rock may still be made out. Large but much broken areas of feldspar may be clearly seen where but very little of the unaltered substance remains. For the most part this has been changed to an aggregate of calcite and minute, brightly polarizing needles or plates of a colorless micaceous mineral (probably sericite) along with occasional areas of secondary quartz. What was once the pyroxene or hornblende is now a colorless or extremely pale green, scaly mineral which an examination shows to be chlorite. Between crossed nicols it is isotropic or very feebly polarizing. It was separated by the Thoulet solution from the slightly heavier feldspar and as a powder appears pale green. In a closed tube it gives off water abundantly and becomes dark. With hot sulphuric acid it decomposes and gelatinizes immediately; with hydrochloric acid it decomposes slowly, giving a somewhat yellowish solution, from which ammonium-hydroxide precipitates alumina abundantly. There can therefore be no doubt that this mineral is a chlorite very poor in iron, like the nearly colorless pyroxene from which it is derived. Areas of leucoxene are also common through this rock.

No. 11165, taken from a place only a foot or two below the last and undoubtedly continuous with it, is decidedly more schistose. Under the microscope the minerals are essentially the same as in the last specimen, but the mechanical effects here exhibited are much more intense. The feldspar and the diallage are still recognizable, but the colorless chlorite is much more abundant than in any specimen before described. The feldspar areas have a brownish color, even in the thin section and they are pulled and torn asunder in a remarkable manner. Individuals are often pulled out into more than twice their original length, the separation taking place along a series of interlacing cracks which run approximately perpendicular to the schistose structure

of the rock. The spaces between the separated fragments are filled with the chloritic mineral. This rock shows every indication of having been enormously stretched and this process, along with attendant chemical changes, has induced its schistose structure. Although it shows under the microscope traces of the original gabbro structure and of the original gabbro minerals, no one would hesitate from a microscopical examination to class it with the schists.

The schists above mentioned as occurring between the two masses of typical gabbro, *h* and *f*, at the Sturgeon Falls, possess an important relationship to these rocks. Taken by themselves, they offer as representative examples of fissile, silky, hydro-mica or sericite schists as could anywhere be found, and yet this narrow band presents such a complete series of transition forms that their origin as derivatives of the massive rock cannot be doubted. In fact, two such series were traced out in detail. One of these was collected on the lower side of *h* and represents the passage of the least altered and most massive gabbro into the typical schist, and the other was obtained near the center of the schist band where a narrow strip of the rock has happily been preserved from the extremest alteration and plainly shows its identity with the gabbro proper. This narrow layer, represented on the map at *g*, is of great value in conclusively proving the origin of the schists in the midst of which it lies and into which it passes on both sides.

No. 11160, from this locality (*g*), was classified in the field-notes with the schists, and regarded as only a harder and more slaty form of these. Indeed, this rock is very schistose, cleaving readily in a direction parallel to the foliation of the more fissile schists. Under the microscope, however, an original gabbro structure is still distinctly seen. Triclinic feldspar, in broken and bent crystals, is plainly visible, while the other constituents have passed into colorless chlorite, quartz and calcite. The feldspar itself is mostly altered into the same compounds, though its form and occasionally its twinning striæ are still preserved.

No. 11161 is a hard, greenish slate, occurring beside the last described rock. Under the microscope, in ordinary light, crystal forms are seen outlined in a dark color, the matrix being colorless. In polarized light, however, these are no longer visible, and there is only a fine grained and schistose aggregate of colorless chlorite, quartz and calcite.

Nos. 11159 and 11158, collected just below the last, are typical schists of a light gray color and somewhat greasy feel. They contain just the same minerals as the rocks last described, but here every trace of original structure has disappeared. There is no indication of the form of any earlier constituents, but those now present are arranged in a finely parallel mosaic of somewhat varying grain. Calcite is much more abundant than in the previous instances. Indeed, in No. 11158 this mineral makes up a large share of the rock.

The other series of transition forms between the gabbro and the

schists occurs on the lower side of the gabbro mass *h*. This series embraces the specimens of the first, second, and third stages of the gabbro already described from this exposure, and terminates with two specimens of schist, Nos. 11163 and 11164. Any sharp line of demarkation between the typical and massive saussurite-gabbro at *h*, and the fissile, silvery schists, apparently so different, lying below it, was sought long and carefully, but in vain. In fact no such line exists, and if one were to be drawn it must be drawn arbitrarily. The rocks already described from this locality as specimens of the gabbro in the third stage show this. No. 11165 is entered in the field-notes as belonging to the schists, but microscopical examination shows it to be even more closely allied than the almost massive No. 11166, to the gabbro. Traces of the original components and structure are by no means rarest in those rocks which appear macroscopically to have suffered the most profound alteration.

Nos. 11164 and 11163 are light gray, silvery schists, with a somewhat greasy feel; such in fact as might ordinarily be classed as sericite or hydro-mica schists. Their lamination, however, is not in the least regular, but undulatory, and there is a tendency to cleavage not so much along a single plane as in almost any plane parallel to a line. In other words, these rocks have a well marked dip, but hardly any determinable strike. In 11164 especially, there is noticeable a jointing transverse to the strike, and these joint planes often gap open into wide, lenticular seams, as though the rock had been stretched in the direction of its strike.

Under the microscope these rocks are seen to be mostly composed of the nearly colorless chlorite, calcite, and a little secondary quartz. These minerals are interlaced in narrow, wavy bands, producing what may be called after the German idiom, a long "micro-flaser" structure. But even here every trace of the original constituents has not yet disappeared. Occasional battered and broken feldspar remnants are encountered, with their fragments widely separated, and for the most part changed to sericite or calcite. Around these curve and twist the silky chlorite bands developing a sort of "Augen" structure, which may be best seen by examining a section with an ordinary pocket lens. The areas of leucoxene also, before observed, are not lacking here, but these are pulled out in the direction of the schistose structure, until a single one may be followed nearly across an entire section. The bisilicates have evidently all passed into the colorless chlorite, and this mineral on account of its pliability has easily accommodated itself to the circumstances, and has developed the pronounced schistose structure which is now the most important feature of the rock.

These rocks are schists, indeed, of the most characteristic type, but in the light of their field relations and still more from the evidence which a microscopical study of the whole series has afforded, it is evident that they represent the most altered form of the massive gabbro, between two areas of which they are included.

Chemical analyses.—In order to ascertain what changes have taken place in the chemical composition of the Sturgeon Falls gabbro during the process of its alteration into the schists, the following analyses of specimens illustrating three successive stages of the alteration were made by Mr. R. B. Riggs:

	I.	II.	III.
SiO_2	51.46	38.05	45.70
Al_2O_3	14.35	24.73	16.53
Fe_2O_3	3.90	5.65	4.63
FeO	5.28	6.08	3.89
CaO	9.08	1.25	4.28
MgO	9.54	11.58	9.57
Na_2O	2.92	2.54	.55
K_2O	.24	1.94	3.82
H_2O	3.30	7.53	4.70
CO_2	.20	.93	5.95
Total	100.27	100.28	99.62

Rock powder dried at 105° C.

I. No. 11170, freshest gabbro from the point *h*.
II. No. 11166, gabbro in third stage from the south side of *h*.
III. No. 11164, silvery schist from between *g* and *h*.

At first glance these analyses seem to present a curious anomaly. The intermediate rock, No. 11166, appears to differ more from the original type than the most altered specimen, No. 11164. A closer examination, however, shows that the nature of the chemical processes which have gone on in the two cases is essentially different. In the first case, No. 11166, this has been chiefly chloritization, while in the second case, No. 11164, the chloritization has been less, but sericitization and carbonatization have also been extensive.

The abundance of the colorless chlorite, above described as present in No. 11166, here manifests itself in the very low percentage of silica and in the correspondingly high percentage of alumina, together with the increase of both magnesia and water. The iron is unusually low in this chlorite because it did not exist in the mother rock; still there has been a gain rather than a loss of this ingredient. The lime has here been to a great extent removed, presumably in the form of the soluble bicarbonate, while the slight sericitization, above mentioned in the description of this rock, is indicated by the increase of the potash.

In the analysis of No. 11164, the less extent of the chloritization is shown by the less, although proportionate, increase of alumina and water and decrease of silica, while the iron and magnesia remain about the same as in the mother rock. Here the lime has been partly removed as before and partly retained as calcite, visible everywhere through the rock and indicated in the analysis by the 5.95 per cent of CO_2. The sericitization, so apparent under the microscope, is here shown by the great increase in potash and the exchange of the soda for potash.

LOWER OR LITTLE QUINNESEC FALLS.

The rock exposure of Lower Quinnesec Falls is not confined to the immediate vicinity of the falls but it extends, especially on the left bank of the river, for a considerable distance below. This portion forms a high, abrupt and homogeneous ridge, of uniform composition and structure, the description of which may be advantageously separated from that of the rocks occurring immediately at the falls.

We shall, therefore, consider under two successive heads:

(1) The greenstones of the so-called "*Gabbro Ridge*" of Major Brooks.

(2) The greenstones of the Lower Quinnesec Falls.

Greenstones of the so-called "Gabbro Ridge" of Major Brooks.—For a mile below Lower Quinnesec Falls, the north bank of the river is skirted by an almost perpendicular wall of massive greenstone. This wall is sometimes over a hundred feet in height, and has every appearance of being a great dike. Although for the most part it is quite massive, it presents frequent and very instructive evidence of the effect of great pressure upon it. It is seamed and gashed, broken and torn, and contains schistose bands of varying width. Since the continuity of these bands with the massive rock is established, their study is calculated to throw light on the subject of dynamical metamorphism.

Major Brooks designated the rock which composes this ridge as a "massive gabbro," and correllated it with the above-described saussurite-gabbro of Sturgeon Falls. My studies have, however, failed to disclose in this rock any trace of pyroxene. In addition to its feldspathic constituent, which is generally altered to saussurite, it contains in abundance that peculiar pale green and more or less fibrous variety of hornblende which is quite universally conceded to be of secondary origin. What the primary form of all this green hornblende was, it is now impossible to ascertain with certainty. It is of a kind well known to originate from the alteration of pyroxene. The rock as a whole also bears decidedly the character of a diabase or pyroxene rock; and yet, not a trace of pyroxene has been discovered in any of the Menominee River greenstones, if we except the light colored diallage of the Sturgeon Falls gabbro. Whenever the pale green hornblende can be traced back to an original form, it is seen to be derived from a compact brown or basaltic hornblende. This fact was substantiated not merely for the rock composing the ridge here under discussion, but it is also true for the several other localities examined on the river.

This brown hornblende is seen first to turn green by a reduction of its iron to the ferrous state, or to become bleached by loss of its iron, and finally to break up into an aggregate of fine hornblende needles exactly similar to that commonly formed by the alteration of pyroxene to uralite.

It is, of course, impossible to prove that some of the secondary fibrous hornblende has not been derived from pyroxene. Indeed, it seems very probable that both augite and compact, brown hornblende may have

existed side by side as original constituents of the rock, and that both finally succumbed to the same process of alteration, although the hornblende resisted this much longer than the augite. Such, in point of fact, has elsewhere been observed to be the case where both minerals have undergone uralitization in the same rock;[1] and this would account for the frequent survival of brown hornblende cores where every trace of pyroxene had disappeared.

If this is not the true explanation of the genesis of these rocks, there are but two other hypotheses possible—either that the original rock contained no pyroxene, but was a diorite, composed of plagioclase and brown hornblende; or, that the pyroxene has passed into uralite through an intermediate compact, brown hornblende. Opposed to the first of these suppositions is the structure of the rock, which is diabasic rather than dioritic. On the other hand, considerable evidence afforded by various of the Menominee rocks, as well as observations made elsewhere by the writer[2] and by Lossen,[3] indicate that the latter hypothesis may possibly be true. Inasmuch, however, as the rocks here under discussion afford no trace of pyroxene, it hardly seems justifiable to call them anything but diorite. We shall encounter still more distinct examples of this type farther up the river.

All the specimens collected from this greenstone ridge show an advanced stage of alteration. Some obtained from the western extremity of the ridge, near the Michigan bank of Lower Quinnesec Falls, have a coarsely porphyritic structure, and are among the freshest specimens that were procured. This variety of the rock is represented by Nos. 11034, 11035, and 11098. Of these the last is perhaps the most typical. To the unaided eye it shows a light greenish gray matrix, thickly studded with irregularly shaped crystals of opaque white feldspar (saussurite) from one-half centimeter to two centimeters in diameter. A closer examination reveals many brightly reflecting cleavage surfaces of another and darker mineral. These are of about the same size as the feldspar crystals, but their continuity is interrupted by small opaque spots, which produce the mottled structure recently termed by the writer *pœcilitic*.[4] The color of these cleavage surfaces, which with the aid of the microscope are found to belong to large individuals of a somewhat altered hornblende, is so nearly like that of the groundmass of the rock that unless their reflection is caught in just the right light they escape detection.

The large porphyritic crystals of feldspar are almost wholly changed to saussurite. This has a dull gray color, and is nearly opaque even in the thinnest sections. A high magnifying power resolves it into an aggregate of minute zoisite needles. Curiously enough, these feldspar crystals show a clear zone of unaltered substance around their outer edge.

[1] Bull. U. S. Geol. Survey, No. 28, p. 45.
[2] Am. Jour. Sci., 3d series, vol. 28, p. 262, Oct., 1884.
[3] Jahrbuch preuss. geol. Landesanstalt für 1883, p. 632, Berlin, 1885.
[4] From ποικιλος, mottled. See Am. Jour. Sci., 3d series 1886, vol. 31, p. 30.

This fresh and finely striated portion presents a striking contrast to the dull gray saussurite, and it is difficult to imagine how it has so completely escaped the alteration which has attacked the rest of the crystal, unless it is the product of a more recent growth.

With the exception of groups of ilmenite grains, which are beautifully fringed with a leucoxene border, the remainder of this rock is composed almost wholly of hornblende. In its freshest state this mineral has a compact structure and coffee brown color, with the usual pleochroism and other optical properties of the species. Its first phase of alteration consists in turning green, and this is followed by a gradual bleaching. This process continues until the mineral has become quite colorless, without, however, losing its compact structure. In the larger individuals of compact hornblende, whether this is brown, green, or colorless, occur numerous small lath-shaped feldspars, which produce the mottled or "pœcilitic" structure above alluded to. These seem to be less completely changed to saussurite than the larger feldspar crystals, but they often contain the zoisite crystals in a more perfect state of development.

It has already been mentioned that these hornblende crystals show an advanced stage of alteration. The hornblende itself is bleached until it is nearly colorless. The final change seems to be the breaking up of this bleached hornblende into an aggregate of colorless needles, resembling tremolite. In other cases, however, it is changed in irregular patches to a colorless chlorite which is quite isotropic, and only visible between crossed nicol prisms. The peculiar manner in which this takes place deserves particular notice, and is represented in Fig. 9. The hornblende substance remains in interlacing veins between the chlorite areas. It is brightly polarizing and may be often seen, as in the figure, to be continuous with an unchanged hornblende individual. This peculiar mode of alteration is doubtless also conducive of the "pœcilitic" effect above mentioned. The clearness, transparency, refraction, etc., of both hornblende and chlorite are so nearly identical that this structure is wholly invisible in ordinary light, and the effect of polarized light in transforming the apparently homogeneous and colorless mass into its two strongly contrasted elements is very striking.

FIG. 9.—Hornblende undergoing alteration to colorless chlorite in a porphyritic diorite from Lower Quinnesec Falls. Nicols crossed. Magnified 80 diameters.

No. 11034 is essentially the same as the specimen just described, except perhaps that it is more altered, and hence contains less of the original compact brown hornblende. Most of the hornblende, indeed,

in this rock is colorless, and much of it is fibrous. That which still retains any color is for the most part green.

No. 11035 was not sectioned, but in the hand-specimen it exactly resembles the others.

No. 11032, collected with the specimens last described, is a beautiful, fresh looking rock, without porphyritic structure, but with its hornblende in long, slender, greenish-black crystals. Under the microscope the feldspar of this rock is seen to be less altered than in those above described. Saussurite is abundantly developed in it, but not so extensively as in the porphyritic crystals of the other specimens. There is, however, here no brown hornblende. This mineral is all of a pale green color, or it is changed to chlorite, which sometimes contains sharp crystals of epidote. Ilmenite is abundant and is fringed with leucoxene.

The above described specimens, from the extreme western edge of the ridge near the falls, although they are the least altered form of the rock, hardly represent its most typical aspect, as the ridge is followed along the river bank, westward from Sandy Portage, its high and almost perpendicular front is found to be composed of a light green or grayish-green, fine grained or aphanitic rock. This is compact and massive in structure, but everywhere profoundly seamed and jointed. It is cut by cross-gashes and parted joints, and gives every indication of having been pulled or crushed—at all events, of having been subjected to enormous mechanical strains. The joints and seams often run in many different directions, producing a regular breccia without cement. The rock is also much slickensided, frequently so much so as to produce a schistose structure. The layers thus formed sometimes bend around more massive cores, which seem to have resisted the rubbing action.

The formation of what are above described as "cross-gashes" is very curious. At times the entire face of the rock wall is scarred with approximately parallel gaping seams, closely resembling the rents formed in moderately dry clay or putty when this is stretched. A single opening does not extend for any great distance, but a great number of them of all dimensions, closely crowded together, may produce an irregular sort of foliation. The general appearance of a rock thus gashed is represented in Fig. 10, which was drawn from a hand-specimen. This of course can give only an approximate idea of the appearance of this structure in a large rock-mass. These gashes seem to have been produced by a stretching of the rock, or, what amounts to the same thing, by a bulging perpendicular to the action of some great pressure. They resemble the "*klaffende Risse*," described by Heim in the Alps, and already mentioned in Chapter I (p. 43). The edges of the seams are ragged as though they had been formed by a forcible tearing asunder of the rock after it was solid. They are often filled with subsequent infiltrations of secondary minerals, like calcite or quartz, but more frequently they are open.

No. 11028 is a fair average specimen of the rock composing this ridge. It is a grayish green, compact, homogeneous mass, which is but little jointed. Under the microscope it is seen to be mainly composed of a

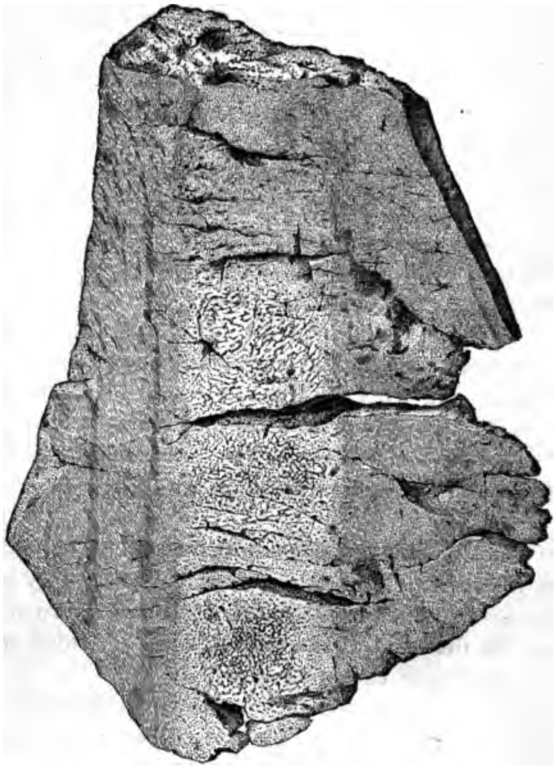


FIG. 10.—"Cross-gashes" in a greenstone from Lower Quinnesec Falls.

finely fibrous, pale green hornblende of secondary origin, of saussurite, quartz, and ilmenite. The structure of the rock has been almost entirely destroyed in the course of the mineralogical changes which have taken place in it. As the new minerals have formed they have wandered from the position occupied by the older ones and have thus produced a fine grained and confused aggregate in which remains of larger rectangular feldspars or hornblende crystals are only rarely discernible. The ilmenite is scattered about in minute dots, each surrounded by its own leucoxene border. The quartz is in irregular patches and bears every evidence of being secondary in its origin.

No. 11033, from near the western end of the ridge, is almost identical with the specimen last described, but contains more quartz, and the remains of the feldspar imbedded in a dark gray, opaque matrix.

No. 11031 is a specimen collected from very near the spot where No. 11028 was obtained, and the two, when taken in connection, show in a very clear and beautiful manner the effect of mechanical action in modifying both the macro-structure and the micro-structure of a solid rock.

In spite of great present differences, there can be no doubt that the two specimens were once portions of a continuous mass. They were taken side by side from a single ledge which showed nothing like a line of contact between two different rocks. One is a typical massive greenstone, with hardly a joint-plane visible in it; the other, while agreeing closely with the first in color and texture, is deeply cracked, gashed and seamed, and possesses a pronounced schistose structure. The original form of both specimens was doubtless an igneous rock of the diabase type, which has been subjected in one case (No. 11028) to chemical (metasomatic) and in the other (No. 11031) to dynamic metamorphism.

Rocks may be altered by simple pressure, but the accumulated strains which are generated within them are relieved and adjusted by overcoming the force of cohesion along certain planes. Here there will be a shearing motion of greater or less extent, and a consequent crushing of the rock. The rent is soon healed by the crystallization of new compounds which cement the crushed fragments, and in this way a schistose band, of width varying with the intensity of the force, may be developed in the midst of an otherwise solid and massive rock; or a number of such bands may be formed parallel to one another, and together imparting to the rock the appearance of a foliated or even a banded schist.

Conclusive proof of this process might be difficult to discover without the aid of the microscope, but this instrument is happily able to afford sufficient evidence to overcome all doubt. We shall have many instances of such action to describe in the sequel, each of which will exemplify some particular phase of the process.

The two rocks here under discussion, however, illustrate this general principle in an admirable manner. Plate IX represents the appearance of each of them in a thin section as seen under the microscope. The structure of the first, No. 11028, is, as above described, a granular aggregate of fibrous hornblende, chlorite saussuritized feldspar, quartz, and ilmenite, produced by chemical action alone in recrystallizing the elements of the original constituents in new compounds more in accordance with the altered physical conditions to which the rock was subjected. The component minerals of the second rock (No. 11031) are not so different from the last, but the story of its origin is told in its structure. The primary constituents seem to have been literally pulverized by crushing. The feldspar crystals have been pulled apart, the fragments being separated a considerable distance (always, however, in the same direction), but it is still possible to recognize fragments which once belonged together. The substance of this feldspar is remarkably fresh, another instance of the chemical action which takes place in this mineral being inversely proportional to the mechanical action which has affected it. The separation of the feldspar fragments is due to a stretching action and the spaces between them are filled with a pale green and almost isotropic chlorite. This mineral has

evidently been developed at the expense of the hornblende, which is here only rarely to be found, and then always in bands where the mechanical deformation has been less intense. Where it is found, however, this hornblende is identical with that occurring in No. 11028. The ilmenite and leucoxene are seen as before, but the former is far less abundant while the latter is proportionately more abundant. When the ilmenite has completely disappeared, the leucoxene forms bands and stringers, thus aiding in the production of a schistose structure.

This development of chlorite out of the hornblende substance seems to be a very important feature in the stretched basic eruptive rocks and many other instructive examples of it will be given beyond. It has a definite bearing upon the origin of the fine grained chlorite schists which accompany and are interstratified with so many of them.

Nos. 11041 and 11042 form an instructive pair of specimens, collected near the river bank toward the western end of the ridge. At this particular locality there is a well marked band of green schist traversing the here generally massive greenstone in a direction S. 70° E. The schistose structure is irregular and undulatory, and on either side there is a gradual passage from the schist into the massive rock. No. 11042 is from the surrounding mass immediately at the edge of the schist band. In a hand-specimen it appears to be considerably altered, of a gray color, and without any cleavage. Under the microscope the original structure is easily recognizable. The rock is largely composed of stout rectangular feldspars, with a somewhat rounded outline, and internally changed to saussurite, though their periphery is mostly clear. Between these are the remains of former hornblende (possibly pyroxene) individuals now represented only by amphibole fibers and chlorite. Beautiful skeleton forms of leucoxene, composed of three sets of parallel bands, reproducing the rhombohedral parting of the original ilmenite, are abundant.

No. 11041 is the same rock as the last in a much more altered form. The feldspar is mostly changed to calcite, and the hornblende to chlorite. The structure has wholly disappeared and there is a very fine mosaic of quartz and secondary albite substance. Still, the same skeleton forms of leucoxene remain and there is no doubt that the two specimens represent the same rock in different stages of alteration, the more changed form having become decidedly schistose.

Farther west, in the immediate vicinity of Lower Quinnesec Falls, the abrupt face of the diorite ridge proper retires a short distance from the river bank. Along the shore the massive greenstones give place to slaty rocks, which cleave into rhomboidal prisms. They have no proper strike, but seem to break with equal readiness in all planes parallel to a line; and this line is here nearly perpendicular to the surface. No. 11043 is one of these rocks of a greenish color. Under the microscope it is seen to have been so profoundly altered that it is now impossible to assert from internal evidence what its original character was. Still, its geo-

logical position indicates that it was once a part of the gabbro or diorite ridge, and there is nothing in its present structure that directly contradicts this supposition. The rock has a pronounced, although irregular and undulatory, schistose structure. It consists largely of a fine grained matrix, composed of chlorite scales, arranged parallel to the direction of schistosity. With this mineral are associated quartz, feldspar, opaque black grains, probably magnetite, and occasionally sharply defined crystals of muscovite. Imbedded in this groundmass are larger feldspars, sometimes in well developed crystals, sometimes in fragments. The substance of these is but very little altered, and yet their outline is made indistinct by the penetration into them of the chlorite scales. They often appear to have been much squeezed and broken, the fragments being more or less separated. Grains of quartz are occasionally seen, which have also been fractured by pressure. Calcite, due to alteration, is also sparingly present.

Similar rocks, more or less schistose and varying from a dark green to a light gray, occur from this point along the river bank all the way to the falls.

No. 11046 is from the light silvery-gray, greasy-feeling band, which projects into the basin at the foot of the falls. This is a typical sericite schist. Under the microscope it is seen to have a finely schistose structure, produced by the parallel arrangement (often in bands) of quartz grains, sericite scales, and chlorite, which is nearly colorless. Along with this is a large amount of calcite, also distributed in bands. There is no feldspar visible. The most interesting constituent is rutile. This mineral is sparingly distributed through the whole rock in very minute and sharply defined crystals. These have a pale yellow color, a high index of refraction, and the usual twinned forms. In certain portions of the section there are dull gray, opaque spots, which are yellow in reflected light. These are not continuous, but are more or less broken up and pulled out in the direction of the schistose structure. They contain occasional dark red and irregularly shaped grains of rutile, but for the most part they are composed of innumerable small rutile needles (quite like the "*Thonschiefernadeln*" of the Germans) so closely crowded together as to form an opaque mass, only resolvable with a high power of the microscope. From these dense masses the other little needles in the other parts of the rock seem to have wandered.

This rock is almost identical with certain light colored, very fissile schists occurring on the opposite side of the river (cf. No. 11011, described beyond), and the strike of these two exposures seems to identify them as belonging to a single band.

Greenstones of the Lower Quinnesec Falls.—Passing now to the rocks exposed along the northern or northwestern shore of the basin below Lower Quinnesec Falls, we find alternating bands of lighter and darker colored greenstones, each accompanied by schistose layers, which present instructive examples of dynamic metamorphism.

The accompanying map (Pl. IV) represents an enlarged portion of Major Brooks's map of Lower Quinnesec Falls. Commencing at the western corner of the basin there are, along its northern shore, three bands of dark and two of light colored rocks. The two kinds of structure, massive and schistose, are so intimately connected in both of them that it is impossible to escape the conviction that the latter has been secondarily developed.

If we begin at the extreme western end of this exposure, at the corner of the basin where a sharp bend in the river's course has produced a low, sandy beach, we discover that the rocks are of a dark green color. The first specimen taken from this band (No. 11001) is massive and jointed. No feldspar is visible, except in large porphyritic crystals, which are not common. Even in this massive rock occasional narrow bands, having a wavy foliation, may be seen. These resemble slickensides, and represent planes of slipping or sliding in the massive rock (No. 11002). Tracing these rocks a short distance to the east, the wavy schistose bands become more and more numerous, until the whole mass becomes decidedly slaty, and has a greasy feel. This foliated rock strikes slightly south of east and dips steeply toward the north. The laminæ are frequently separated and bulged into lenses, which are either filled with quartz or are still open and then coated with drusy quartz (No. 11003). These slaty rocks have a dark gray color, and, in some respects, resemble hydro-mica schists, but yet it is impossible to separate them in the field from the dark green massive rocks above described, *as each passes by insensible gradations into the other.*

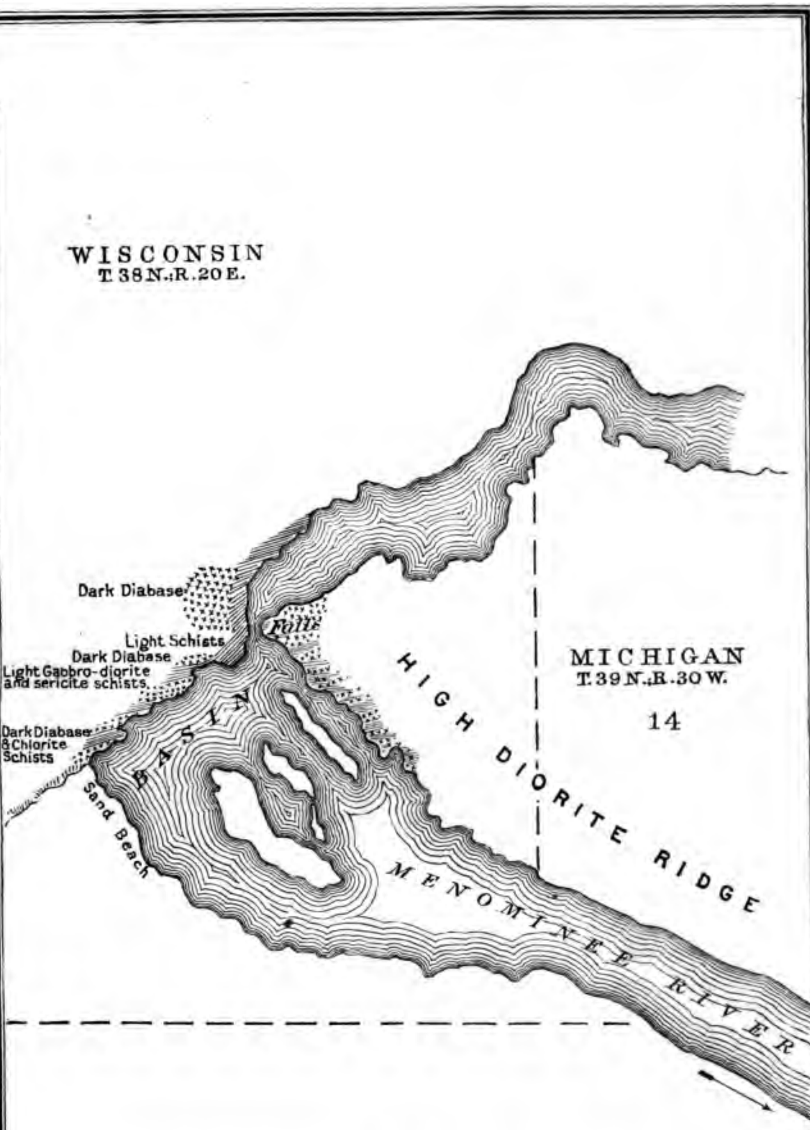
Under the microscope, No. 11001 appears as a medium grained aggregate of feldspar and pale, fibrous hornblende with some ilmenite and leucoxene. The structure is still well preserved. The feldspar is in stout, columnar crystals, all distinctly striated and often considerably changed to zoisite or epidote. The hornblende is in irregular, ragged masses or in minute needles. The pale, fibrous sort is plainly seen to have been derived from a compact, darker green and pleochroic variety; but farther back than this (i. e., to a possible original pyroxene) it can not be traced. There is also a little pale green chlorite, looking much like the secondary hornblende, except between crossed nicols, where it is nearly isotropic.

No. 11002, taken from one of the narrow schistose bands, has plainly been produced by a shearing or sliding within the last described massive rock, and presents an interesting relationship to it when placed under the microscope. The two are plainly identical as far as the component minerals are concerned, but the structure of the latter has undergone a great change. The grain at first glance appears to be finer, but this is soon seen to be due to a crushing of the original minerals. The feldspars especially are very much broken and their parts more or less separated. This mechanical action has been attended by increased chemical activity. The original substance of the crushed feldspar crys-

tals is hardly as much changed as in the preceding instance, but there has been a considerable recrystallization of new feldspar substance (probably albite). The hornblende, because of its secondary nature, is more like that in the massive rock (No. 11001), but even this is sometimes sundered and torn. Chlorite is much more abundant, especially in the interstices between the fragments of the broken feldspar crystals. It is sometimes filled with very delicate and minute, though extremely sharp, epidote crystals. The ilmenite is more extensively changed to leucoxene than before, and, in some cases, shows a decided pulling out in the direction of the schistose structure. On the whole, many of those metasomatic changes which the greenstones most commonly show are here seen to have been accelerated and intensified by the mechanical force which has crushed the rock and so changed its structure. Thus the two forces—dynamical and chemical—may go hand in hand and together produce a rock which is both structurally and mineralogically very different from that out of which it has been derived.

Passing eastward along this exposure, we next come to a wide band of much lighter colored rock, which extends as far as the lower side of the small cove, situated on the right bank immediately below the falls. This band exhibits, in a most admirable manner, the secondary development of schistose layers in a massive rock, and is well deserving of careful study. The most typical and least altered form occurs just at and below the corner of the small cove. This is a medium grained, massive aggregate of opaque white saussurite and light green, fibrous hornblende, and it closely resembles, in its external aspect, the barrier rock at both Upper Quinnesec and Sturgeon Falls. Nos. 11008 and 11009 represent this occurrence, but even the most massive specimens which could be obtained are seamed with cracks approximately parallel in direction and coated with a lamellar, soft green mineral like that in the adjoining schists. This is shown by examination to be chlorite. On both sides of the massive portion of this band the parallel cracks become more and more abundant (No. 11004 below, and No. 11010 above), and on the lower side of the small cove the rock passes, without any break in its continuity, into silky schists (No. 11011), like those above described from the opposite side of the river (cf. No. 11046, p. 84).

Under the microscope, the least altered specimens of this rock (Nos. 11008 and 11009) are found to bear a close resemblance to the light colored gabbro of Sturgeon Falls (see p. 68), except that in the present instance no trace of diallage is discernible. The structure of the two rocks is the same. The feldspar is here also replaced by the same gray, opaque saussurite, in which, with a high power, zoisite and calcite may be easily detected. The hornblende, as seen in a microscopic section, is practically colorless. Only occasionally are traces of a greenish tinge observable. Between crossed nicols this mineral generally exhibits a homogeneous extinction, so that it can not be regarded as truly fibrous, and yet there can be no doubt as to its secondary nature. Its edges are



MAP
of
LOWER QUINNESEC FALLS
Menominee River
(After Brooks)
SCALE

0 500 1000 1500 2000 2500 Feet
0 ⅛ ¼ ⅜ ½ Mile

ragged and there is a decided tendency to separation into fibers, even when these are not actually present. It is noteworthy that this secondary hornblende can only be traced back (and that in rare instances) into a more compact greenish or brownish variety of the same mineral. In none of the thin sections is there any positive evidence that diallage was ever present; and yet the close similarity of this rock to the Sturgeon Falls gabbro naturally suggests it. If the diallage were originally present it has completely changed to the pale hornblende, while the brown hornblende longer resisted the bleaching action, and hence sometimes still remains. If this were not the case, we are compelled to assume one of the two other alternatives suggested in the case of the porphyritic diorite from the other side of the river, No. 11098 (see p. 78).

The pale hornblende is often partially altered to colorless chlorite, and the ilmenite is more or less changed to leucoxene.

Nos. 11004 and 11010, taken from either side of the above described band, represent somewhat schistose varieties of it which have been produced by the action of pressure. That this is actually the case is admirably shown by a microscopic examination. The hornblende of the original rock seems to have passed completely into a very pale or colorless chlorite. Saussurite, on the other hand, is less abundantly developed than in the more massive rock above described, and it is disposed in narrow veins or in small, irregular spots. The ilmenite has given its place to a dark gray substance resembling leucoxene. This is drawn out in stringers following the direction of the schistosity, and in the center of these a yellow grain of rutile may sometimes be observed. Calcite is also present. The structure of the rock is completely different from that from which it is supposed to have been derived. It is now composed largely of a fine grained groundmass. This is made up of a microgranitic aggregate of minute grains of an unstriated substance resembling quartz, but which, from its high specific gravity, is probably a feldspar. These grains, together with chlorite scales, leucoxene, some calcite, and an occasional bit of epidote or sericite, are arranged so as to produce an indistinct schistose structure, the bands of which bend and wind around larger porphyritic individuals of feldspar. In this way a lenticular or "Flaser" structure results, which, however, is hardly discernible, except under the microscope. A very particular interest attaches to the porphyritic feldspar crystals of these rocks. In comparison with those in the more massive rock (11008 and 11009), they are but slightly altered to saussurite; indeed, for the most part, they are surprisingly fresh and glassy. Glistening cleavage surfaces may be readily detected with the unaided eye, and under the microscope this feldspar appears in clear, colorless grains, almost wholly free from inclusions of any kind. Occasionally these possess a light brownish tinge, due to some evenly distributed pigment. Between crossed nicols this clear feldspar substance presents sharp twinning lamellæ and a comparatively high extinction angle.

The individual crystals are invariably broken and the fragments are more or less separated. The intervening spaces are filled with a micro-granitic groundmass, as shown in Plate VIII, figs. 1 and 2, of other similar, though more acid rocks from Upper Quinnesec Falls and from the vicinity of Marquette, Michigan.

The clearness and freshness of this feldspar would at first suggest the probability of its being a secondary crystallization, as, for instance, albite is often found to be. This, however, is shown not to be the fact, first, by the broken state of all the crystals, indicating that they must have been in existence when the rock was pressed and crushed; and, second, by their physical properties which show that the feldspar is labradorite. Upon isolation this feldspar was found to have a specific gravity of 2.69; and in cleavage pieces parallel the basal plane, it gives an extinction angle of 12° to 20° on each side of the twinning-trace.

The survival of the original feldspar in an almost unaltered state, in a rock so profoundly changed by mechanical action, naturally occasioned some surprise. Examples of the same sort have already been cited (e. g. Nos. 11154 and 11165 from Sturgeon Falls, and No. 11032 from the diorite ridge below Lower Quinnesec Falls), and so many cases of a like character were encountered from other localities that the occurrence of the freshest feldspar in the most crushed rock must be regarded as the rule.

I know of no way of interpreting this phenomenon, substantiated by so many instances, except by supposing that the pressure, which acts powerfully in stimulating chemical action in the solid rock, is relieved on the harder grains of a crushed band, since these are able to change their position by slipping among the softer materials.

The nearly vertical, silvery schists (No. 11011) which occupy the western corner of the little cove just below the Lower Quinnesec Falls, represent only a more highly metamorphosed state of the rocks above described. They are extremely soft, fissile, and schistose in a hand-specimen. Under the microscope they closely resemble the groundmass of the last described rocks (Nos. 11004 and 11010). The granular aggregate is so disposed as to produce a decided schistose structure. Both calcite and sericite have become more abundant, while the porphyritic feldspar crystals have completely disappeared. The leucoxene also can no longer be found, but the long lines of very sharp and minute rutile crystals, which are not present in any of the more massive related rocks, appear to have taken its place.

The perfect continuity of the massive rock (Nos. 11008 and 11009) with these schists, through the intermediate member (11010) is admirably shown in the exposure at the western end of this small cove.

The following chemical analyses of these three specimens have been made by Mr. R. B. Riggs.

I. No. 11008, Gabbro-diorite from Lower Quinnesec basin.
II. No. 11010, Schistose form of the same rock.
III. No. 11011, Seriate schist adjacent to last.

	(I.)	(II.)	(III.)
SiO_2	47.96	49.19	46.21
Al_2O_3	16.85	18.71	18.38
Fe_2O_3	4.33	5.03	3.30
FeO	4.17	4.04	3.90
CaO	13.25	5.92	6.28
MgO	9.15	7.98	7.03
Na_2O	1.25	1.44*	2.14
K_2O	.30	.77	.35
H_2O	2.89	5.05	3.82
CO_2	.08	1.82	8.32
Total	100.23	99.95	99.73

TiO_2 not determined.

The close agreement between these analyses is striking. The low percentage of iron sufficiently accounts for their uniformly light color. The most striking difference is perhaps the loss of calcium and the lesser loss of magnesium, both of which were undoubtedly carried off in the form of soluble carbonates when the rock was crushed. The water is contained in the pale chlorite, which first increases in amount and then decreases, as its components are transformed into carbonates. The sodium was first contained in the feldspar and the steady increase in its relative amount is probably due to the development of the sericite-like mica, which may be a paragonite.

It is interesting to compare the first of these analyses with that of the Sturgeon Falls gabbro (I on p. 76), the close resemblance of which to the rocks here under consideration has already been alluded to. The only noticeable difference is a slightly larger proportion of silica and a smaller proportion of alumina and lime in the Sturgeon Falls rock.

Passing now still farther to the eastward, we come to the second band of dark-colored greenstones (see map, Pl. IV). These follow directly after the narrow exposure of the above-mentioned silvery schists in the western corner of the little cove and form a great part of its northern shore. They resemble the rocks occurring in the band first described, and present both massive and schistose varieties, which grade insensibly into each other in a manner not less instructive than that in the two bands already considered.

Nos. 11012, 11013, and 11021 (the first two from massive portions of this band along the shore of the small cove; and the last from the Wisconsin side of the river directly opposite the falls) are essentially identical in appearance and composition. In the hand-specimen they form a compact, aphanitic mass, of a dark green color. Under the microscope the originally diabasic nature of the rock is at once apparent, although

the extensive mineralogical changes which have gone on have greatly obscured its former structure. The components now present are almost wholly secondary. These are hornblende, chlorite containing epidote, quartz, and leucoxene. Ilmenite and occasional traces of feldspar are the only original constituents which remain. Still the disposition of the secondary minerals is such as to outline a diabasic or ophitic structure often with great distinctness. The feldspar is rarely well preserved; but a narrow zone of the unaltered substance of this mineral often outlines a stoutly lath-shaped crystal, even when its interior is wholly changed to an aggregate of quartz, chlorite, and epidote. The hornblende has a curious appearance. Its crystals are brownish and nonpleochroic with a somewhat granulated surface, so that it externally resembles diallage. Its cleavage and optical properties prove it to be undoubtedly hornblende, although this superficial likeness to diallage is so strong as to almost compel the conviction that it has originated by paramorphism from a pyroxene. This brown hornblende is seen with a high power to be gradually changing to a green variety, in which a pleochroism for the first time becomes apparent. This also frequently passes over into a fibrous hornblende. The chlorite epidote aggregate in these rocks is very finely developed. The chlorite is of an emerald green color and distinctly pleochroic. It appears between crossed nicols as isotropic or polarizes with a maroon tint. The epidote is in sharp, light yellow crystals, with the characteristic shape and optical properties of this species. The microscopic appearance of this aggregate is represented in Pl. XI, fig. 1, drawn from a specimen collected below the Upper Quinnesec Falls (No. 11049). The literature relating to it has already been cited (Chapter I, p. 57). The epidote crystals have been described from the Menominee region by Wichmann[1] and others as secondary augite. This chlorite epidote aggregate covers considerable areas and occupies the place of both the feldspathic and the pyroxenic constituents. In addition to the minerals already named, ilmenite, with its leucoxene border, pyrite and secondary quartz are quite abundant in these rocks.

No. 11014, taken from a narrow, schistose band in the massive greenstone (No. 11013), shows in a remarkably clear manner how the dynamic metamorphism of this rock has been accomplished. In this instance there can not be the least doubt as to the continuity of the rock-mass. The hand-specimen No. 11014 has a decidedly schistose structure, and under the microscope it shows the effects of mechanical crushing and attendant mineralogical changes with great distinctness. The whole rock, with the exception of certain remains of the larger feldspar crystals, has been reduced to a fine grained mass, showing an aggregate polarization. Light green chlorite has been largely developed and has completely replaced all the bisilicate elements. The parallel arrangement of the scales of this mineral is what produces the schistose

[1] Geol. Wisconsin, vol. 3, 1876, pp. 623, 624.

structure, and it surrounds and incloses the small grains in the manner which has already been explained in connection with No. 11031 (p. 81) and illustrated in Pl. IX, fig. 2. The clear, secondary grains forming this mosaic are certainly, to some extent at least, quartz, while a portion of them may be an unstriated feldspar. Calcite has been largely developed in the schistose rock, and the leucoxene is replaced by rutile, either in stout, yellow grains, or in minute, sharp crystals arranged in long, sinuous lines.

The mechanical action which produced this schistose band has therefore resulted in the crushing of the rock, and the almost total disappearance of all of the original components. The comparatively slight change in the chemical composition of the rock as a whole may be seen from the two following analyses of Nos. 11021 and 11014, made by Mr. R. B. Riggs.

I. No. 11021. Dark massive greenstone, Lower Quinnesec Falls.
II. No. 11014. Dark schistose greenstone, forming a band in the last.

	(I.)	(II.)
SiO_2	43.80	44.49
Al_2O_3	16.08	16.37
Fe_2O_3	9.47	5.07
FeO	10.50	5.60
CaO	7.81	7.94
MgO	6.54	7.50
Na_2O	1.96	2.59
K_2O	0.34	0.56
H_2O	3.99	4.99
CO_2	0.08	5.38
Total	100.57	100.39

TiO_2 not determined.
Powder dried at 105° C.

The changes here are at once seen to be due (1) to the total removal of the iron ores (loss of iron); (2) to the production of carbonates (gain of CO_2, carbonatization); and (3) to the increase in the amount of chlorite, (increase of H_2O, hydration).

Toward the eastern end of the small cove the dark-green schistose rocks appear to pass by insensible gradations into exactly similar ones of a lighter color. No. 11015, one of these, is seen under the microscope to be a very schistose aggregate of extremely pale chlorite and quartz grains. There is a little calcite here present and occasional scales of sericite. The rutile, in very minute and sharp crystals, is here crowded into long bands and stringers which follow the schistosity of the rock and give the thin section a pronounced "Flaser" structure.

No. 11016, from the extreme eastern corner of this cove, represents a band of light colored brownish rocks with a perfectly developed schistose structure and a grain somewhat resembling that of wood. These

stand nearly vertical, though some dip from 65° to 70° N. 20° W. Their strike is turned from that of the other rocks here (S. 70° E) some 30° to 40°, so that they now strike N. 70° E. Under the microscope this rock is seen to have essentially the same structure and composition as the last. The main difference between them is that the present specimen has a brown chlorite instead of a green one. This it is that imparts the peculiar color to the rock in the hand-specimen. There is also more calcite in this rock than in the other. It would seem, along with No. 11011 above described, to represent the most profoundly metamorphosed phases of the massive rocks at Lower Quinnesec Falls. The original constituents have undergone an alteration to chlorite, quartz, carbonates, and rutile. The iron has largely disappeared, and the crystallization of the new components under lateral pressure has produced a very pronounced schistose structure.

No. 11023, from the upper end of the breakwater, above the falls (Wisconsin side), is very closely allied to the two specimens last described. It is a grayish schist, with the prevailing strike, but everywhere seamed with transverse cross-gashes, which are, for the most part, filled with infiltrated quartz. There seems to be little doubt from a field examination, that this rock is continuous with the massive diabase (No. 11021) in the same way that the last mentioned specimens are continuous with Nos. 11012 and 11013. The massive green rock (No. 11021) is exposed a very short distance to the west of it, where it also is filled with seams and cross-gashes, which appear to have been squeezed open by lateral pressure. From this point the transition to the gray schistose rock is a very gradual one. The latter rock has no regular bedding but only a cleavage in one direction. This causes it to break out in angular prisms. The rock is everywhere fissured, slickensided, and filled with infiltration quartz, as evidence of the enormous pressure to which it has been subjected. Under the microscope it is much like No. 11016. There is the same quartz mosaic, pale chlorite and strings of rutile needles, arranged so as to produce a decided schistose structure. There is, however, in this rock considerably more calcite and an additional feature in the way of remains of former feldspar crystals. These are considerably altered, and appear to be changing to a mass quite like that which composes the rest of the rock. In fact, this has gone so far that it is almost impossible to distinguish these feldspars in ordinary light, although their outline and nature become very apparent between crossed nicols. They are arranged without reference to the present schistose structure of the rock, and evidently represent original constituents of the rock from which the present schist has been derived.

In place of the above-described transition from massive to schistose rocks along a line—normal to the strike—there is in many instances the still more conclusive proof to be found in this same transition around ellipsoidal or lenticular cores of massive rocks. Such masses grow gradually schistose around their periphery and pass into schists which ap-

pear to wind around and enclose them, but which, in reality, have been formed out of their own substance. An admirable example may be seen just at the Wisconsin edge of the river at the foot of Lower Quinnesec Falls. This is a lenticular mass of massive greenstone about eight feet in its longest diameter. This grades insensibly around its edge, into dark green schists, differing only in their structure from the central rock. Four specimens (Nos. 11017, 11018, 11019, and 11020) were collected to illustrate this passage. The most interior and massive one (No. 11017), although to all appearances quite compact, is found upon a microscopic examination to be wholly altered mineralogically. The bisilicate constituents are now represented only by a light emerald-green, pleochroic mineral, which, in spite of its comparatively strong action upon polarized light, is probably chlorite. This frequently contains sharp epidote crystals. The feldspar, while retaining much of its original form, is composed either of a gray, opaque saussurite or of a fine mosaic of quartz and albite grains and a great deal of calcite.

The extremely altered condition of the central portion of this core is perhaps rather advantageous than otherwise, for, while there can be no doubt as to its original character, the transition to the schists is seen to take place wholly by a change in structure, without further mineralogical alteration.

No. 11018, taken from a place where indications of a schistose structure are already quite apparent, shows just the same mineral components as the last. The chlorite scales, however, have assumed a decidedly parallel arrangement, which is followed, to a less extent, by the fine mosaic of quartz and albite grains. The calcite is better crystallized, and forms larger individuals. There are also present some minute scales of a deep red iron oxide, probably göthite, or limonite. The gray saussurite is likewise common.

No. 11019, in which the schistose structure is still more apparent, shows the same components as the others. The parallel arrangement of the chlorite is still more pronounced and the calcite still better crystallized. Strangely enough, we meet here, in a very schistose rock, better preserved feldspar crystals than can be found in the more massive greenstone, with which it is so intimately connected. This is but one more instance of the remarkable rule set down on p. 88, and alluded to several times already. This thin section (No. 11019) exhibits feldspars so well preserved that only occasional epidote crystals are developed in them. There is also to be seen a remarkably good example of the change of pyrite to iron hydroxide.

No. 11020 represents the extreme member of this series. It is a typical chlorite schist, in which alternating and interlacing areas of pale green chlorite and a fine quartz albite mosaic may be seen. In both a highly developed schistosity is produced by the parallel arrangement of the components. The grain of this rock, in so far as it is due to these alternating areas, appears somewhat coarser than in the less altered forms.

CHAPTER III.

GREENSTONE BELTS OF THE MENOMINEE DISTRICT—(Continued).

UPPER OR BIG QUINNESEC FALLS.

About 3½ miles above Lower Quinnesec Falls, described in the preceding chapter, the course of the Menominee River is again interrupted by extensive rock exposures, which skirt the banks for nearly 2 miles. The upper mile of this distance is a high, rocky gorge, known as the "Horse Race," through which the water rushes and tumbles in a foaming rapid. The current then flows more quietly through a broader, though still rocky channel, for half a mile, when it suddenly plunges over a fall of considerable height and beauty, known as Upper or Big Quinnesec.[1]

Below this fall the stream broadens into a wide basin, which is also bordered by rocky shores.

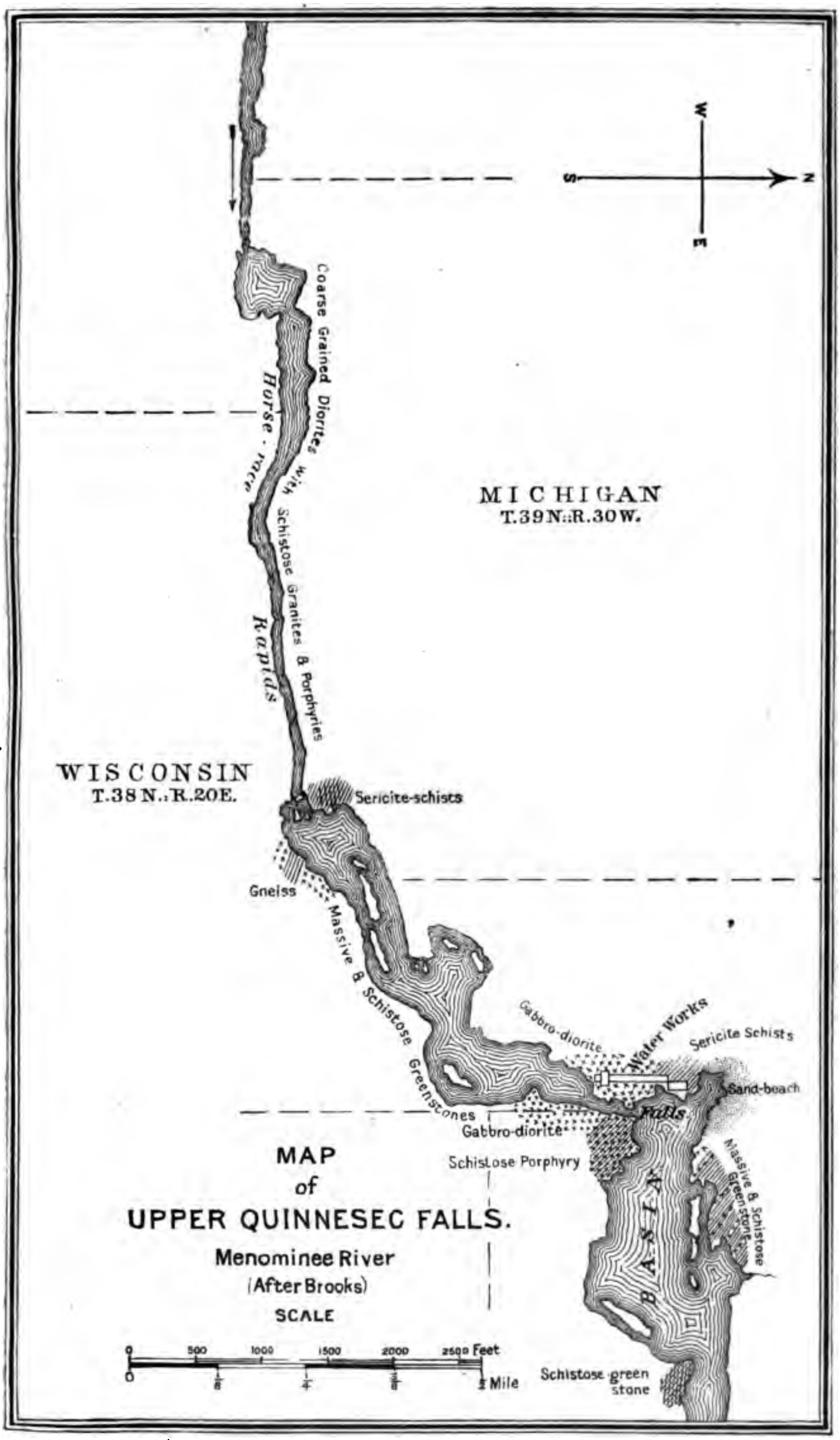
The continuous exposure of Upper Quinnesec Falls is, therefore, separable into three naturally distinct divisions. These divisions are, moreover, each characterized by a different kind of rock; a fact which serves to distinguish them almost as sharply as their physical conformation. (See map, Pl. V.)

The rocks which are exposed along the basin belong, for the most part, to the class of dark, more or less schistose greenstones, similar to those occurring at Lower Quinnesec Falls. These were once diabases rich in iron, which have produced amphibolitic and chloritic schists of a deep green color.

The actual barrier at Upper Quinnesec Falls is, on the other hand, composed of the light colored type of greenstone with a distinctly granular structure, like that already described as occurring at both the Sturgeon and Lower Quinnesec Falls. This is also the commonest rock for the half mile above the falls, before the rapid is reached. It is deserving of careful study on account of the transition which it presents into light colored sericite schists.

The rock which forms the steep walls of the gorge known as the Horse Race is of still a different type. It will receive a separate treatment, as it is quite unlike anything observed elsewhere in the Menominee Valley.

[1] This name is a corruption of the Chippewa *Bequenesec* which is spelled by H. Credner in his description of this locality as *Bekuenesek*. (Neues Jahrbuch für Mineral., 1870, p. 971.)


W
S
N
E
Coarse Grained Diorites with Schistose Granites & Porphyries
Horse-race Rapids
MICHIGAN
T.39N.:R.30W.
WISCONSIN
T.38N.:R.20E.
Sericite-schists
Gneiss
Massive & Schistose Greenstones
Gabbro-diorite
Water Works
Sericite Schists
Sand-beach
Falls
Gabbro-diorite
Schistose Porphyry
BASIN
Massive & Schistose Greenstone
Schistose green stone
MAP
of
UPPER QUINNESEC FALLS.
Menominee River
(After Brooks)
SCALE
0 500 1000 1500 2000 2500 Feet
0 1/8 1/4 3/8 1/2 Mile

Finally bands of certain acid rocks—granites, gneisses, and schistose porphyries—occur in the greenstones both at the fall and along the Horse Race. They appear to stand in the closest genetic relation both to each other and to the great granite area which lies south of the river and approaches it at this point more nearly than at any other.

We may, therefore, consider the rocks of Upper or Big Quinnesec Falls under the four following heads:

(1) The dark colored greenstones of the basin.
(2) The light colored greenstones at the falls.
(3) The coarse grained diorites of the Horse Race.
(4) The acid rocks, both massive and schistose.

THE DARK COLORED GREENSTONES OF THE BASIN.

At the lower (eastern) extremity of the basin, below Upper Quinnesec Falls, is an exposure of greenstone which juts into the river from the Wisconsin side. It is of a uniformly green color and, for the most part, massive, although schistose portions are not infrequent, which have the prevailing strike, N. 70° W., and stand nearly vertical. These schistose bands have in the field every appearance of being secondary since they are only locally developed and grade imperceptibly into the massive rock. A specimen from this locality, No. 11049, when examined microscopically, appears to be very similar to a rock already described from the Lower Falls (No. 11048). The process of alteration there indicated, however, has here progressed much further. There is every reason to believe that this rock, like the other, was once a diabase; and yet, in this case, all traces both of the original structure and of the original constituents have disappeared. The feldspar substance is completely replaced by a confused network of epidote needles, or of these mixed with chlorite; some rather compact, green hornblende still remains, but this mineral is rapidly disappearing, and the manner in which, jointly with the feldspar, it furnishes the materials out of which the chlorite-epidote aggregate is formed is here very instructively displayed. In fact, no other rock showed this characteristic form of alteration as well as this one, and it was therefore selected to furnish the illustration. (See Pl. XI, fig. 1.) The titanic iron is here in the form of small grains, accompanied by leucoxene.[1]

On the southern or Wisconsin side of this basin there are no more important exposures of the dark colored greenstones. On the Michigan side, however, such exposures are abundant and have been indicated on Maj. Brooks's map as the points *z*, *aa*, *bb*, and *cc*.[2]

Two suites of specimens collected at these points, one by Prof. Irving

[1] Slide No. 931 of the collection of the Lake Superior Division of the U. S. Geological Survey was prepared from a specimen collected by Prof. R. D. Irving west of the above, among the light colored greenstones. It is of great interest in this connection because its feldspar is quite well preserved and shows in a most unmistakable manner the ophitic structure of the diabases. In other respects especially in the character and abundance of the epidote-chlorite aggregate, it is quite identical with No. 11049.

[2] Geol. Wisconsin, vol. 3, Pl. 3, p. 474.

and the other by the writer, were studied. The rocks all exhibit the effects of extreme mechanical action upon their constituents, which has so far obliterated their original structure as to render their true character doubtful. They agree in being composed of different proportions of a much crushed and altered, reddish brown feldspar and a pale green mass consisting of chlorite and quartz. The latter aggregate is of secondary origin and imparts a cleavage to the rock, since the chlorite flakes are all arranged in one direction.

No. 4162, from Prof. Irving's collection, was the only specimen studied microscopically from point *z*. It is composed mostly of feldspar, and has, therefore, a reddish color. This constituent is intensely crushed and its substance is so highly altered as to appear to grade imperceptibly into the quartz chlorite matrix, which is present in small amount between its fragments. Scattered through this mass in the direction of its foliation are long lines of some opaque iron oxide, accompanied by very minute though sharply defined crystals and twins of rutile (Thonschiefernadeln), like those represented in Fig. 12, p. 106. In some cases the iron oxide is absent, and these dark bands may be seen with a high magnifying power to be made up entirely of the closely clustered rutile crystals.

Nos. 4163 and 11070 are both from Brooks's point *aa*, which he describes (loc. cit.) as composed of a "chloritic greenstone schist, with pinkish grains of feldspar (Schalstein ?)."

The first of these sections belongs to Professor Irving's collection, and exhibits under the microscope the effects of the crushing and stretching in a very marked degree. Its structure resembles that of specimen No. 11102 from the lower Quinnesec Fall, described on p. 94, and represented in Pl. XI, fig 1. White and reddish feldspar crystals, quartz grains, and opaque black spots of iron oxide are imbedded in a secondary matrix consisting of chlorite, quartz, and epidote. No trace of an original bisilicate now remains. All of the older components, especially the feldspar and iron oxide, are much broken and their fragments are separated in one uniform direction corresponding to the foliation of the rock; but yet the fragments which once belonged together can still be recognized. The feldspar substance, in spite of the intense crushing, is still remarkably fresh and its twinning striation distinct. Lath-shaped forms, like those of diabase, are present, though all traces of the original rock structure have disappeared. The opaque grains of iron oxide (magnetite) are broken and pulled apart like the feldspar and can be seen with a high magnifying power to be fringed with minute and imperfectly formed rutile crystals. Sharply defined octahedra of magnetite—evidently of secondary origin, as they never exhibit any traces of mechanical action—are also scattered through the chlorite, and in some cases these octahedra are crowded together with little rutile crystals, both looking as though they had resulted from the alteration of some preexisting mineral.

No. 11070, collected by the writer from the same locality as the last (Brooks's point *aa*), possesses a similar character, though with certain important differences. The hand-specimen is dark green in color and decidedly schistose. Under the microscope it is seen to be essentially the same rock as that last described, but in an even more advanced stage of alteration. The fragments of reddish feldspar, which can still be seen to belong together, are here, as before, separated in the direction of the foliation, while the spaces between them are filled with chlorite flakes and quartz grains. The feature of particular interest in this specimen is, however, the abundance of its rutile and the constant and close association of this mineral with the black iron oxide. This association, as well as the general appearance of this rock under the microscope, is represented in Pl. XIII, fig. 2. The opaque, black grains, which in reflected light can be seen to be intergrown with a considerable proportion of pyrite, are surrounded by a border of stout, brownish yellow needles, averaging from 0.1 to 0.05^{mm} in length by from 0.02 to 0.01^{mm} in width. They are crowded closely together and are often parallel to the external edges of the grains. Not infrequently, also, they exhibit a regularity of arrangement, crossing each other at angles approaching 60° and 120°. It will be readily seen, however, that in a random section of the rock it is impossible to decide whether these are exactly the angles or whether they are the angles 54° 43′ and 65° 35′ (with their supplements, 125° 17′ and 114° 25′), which von Lasaulx has shown are produced by the twinning of rutile, and characteristic of its network growth called as sagenite.[1] An isolation of these needles was made by dissolving all the other constituents of the rock in HCl and HF, for the purpose of obtaining material which might positively decide this point, but no definite results were obtained. The needles are for the most part irregular in their arrangement, and it still remains uncertain whether their occasional regularity is due to twinning or to some other cause.

A chemical examination of the isolated needles showed that they were composed of titanium oxide, while their crystallographic and optical properties observed under the microscope proved them to belong to the species rutile.

The fact that the black, opaque constituent of this rock is traversed by parallel cracks and fissures, often in sets intersecting at an angle of 60°, like those observed in titanic iron, taken in connection with the close relationship of the rock itself to the family of diabases, naturally led to the assumption that the iron oxide was ilmenite. Moreover, the similarity of the distribution of the rutile about the black cores to that of leucoxene about ilmenite crystals in the process of alteration—its presence as a continuous border and in every crack, while the black substance itself is quite free from the needles [2]—seemed further to indi-

[1] Zeitschr. für Kryst. u. Min., vol. 8, 1884, p. 56.

[2] This was shown, not merely by the absence of the larger needles which, if they were present, must have appeared through the black substance of the iron oxide in the thin section, but also by slowly dissolving away the oxide with HCl under the microscope and the failure thus to disclose any smaller crystals of rutile, which might have been wholly inclosed within the black ore.

cate the secondary origin of the rutile out of the ilmenite. This is the view that was at first taken by the writer and published by him in a letter to the Neues Jahrbuch für Mineralogie, etc., 1887, vol. 2, p. 263. In a subsequent paper on the same rock,[1] Prof. Cathrein of Karlsruhe showed, among other points which he considered as objections to the secondary origin of the rutile, that the black iron oxide was not ilmenite at all, but magnetite. This determination has since been confirmed by a careful chemical examination made at my request by Prof. S. L. Penfield, of the Sheffield Scientific School at New Haven.

A very similar occurrence of rutile needles, though inferior in size to those here described, has been observed by Cathrein in the leucoxene border which surrounds both ilmenite[2] and titaniferous magnetite[3] in certain Tyrolese rocks. Dr. J. Blaas also encountered the same kind of a network of rutile crystals in a quartz phyllite from the neighborhood of Innsbruck, but in this case it was unaccompanied by any opaque ore.[4] In none of the instances observed by him does Cathrein consider the rutile as even possibly a secondary product. On the other hand, he thinks that the little needles were formed simultaneously with the ilmenite or magnetite, and that they have always existed in their present form within the iron oxide, until more or less completely liberated by the solution and removal of the latter.

In his article on the Quinnesec rock above cited, none of the points insisted upon by Cathrein appear to militate against the secondary origin of the rutile, except the last. As has been stated above, it is impossible in a random section to determine with certainty whether the needles intersect at angles of exactly 60° and 120°, or at those so nearly like them produced by twinning. But whichever be true, it is certain that a large majority of the needles are quite irregular in their arrangement. The discovery, however, that the black iron oxide which accompanies the rutile is not ilmenite but a magnetite almost free from titanium, seems at first altogether incompatible with the idea that the rutile is a secondary derivative from ilmenite. Nevertheless, a continued and repeated study of a large number of thin sections of this rock have served to convince the writer more and more that the rutile was at least not a constituent of the rock in its original state. The rutile aggregates are never drawn out in the direction of the stretching, as are all of the original constituents, notably the feldspar, and as they must have been had they always been present in the rock. It is necessary, therefore, to assume that they originated subsequent to, or, more probably, at the time of the metamorphism.

The constant and intimate connection between the rutile and the magnetite clearly shows that they are in some way genetically related. Opposed to the supposition that they were originally parallel inter-

[1] Neues Jahrbuch für Mineral., etc., 1888, vol. 2, pp. 151-165.
[2] Zeitschr. für Kryst. u. Min., vol. 6, 1882, p. 248.
[3] Ibid., vol. 8, 1884, p. 321.
[4] Tschermak's min. u. petrog. Mittheil., vol. 4, 1882, p. 514, fig. 2.

growths, is, however, the fact that the rutile needles never occur within the magnetite, now present. The rutile forms a border around the black areas, which themselves frequently show a sharp crystal outline, difficult to reconcile with the idea that they have been partially dissolved so as to reveal the rutile which once existed within them. In one instance, indeed, an aggregate consisting of rutile needles and sharp octahedra of magnetite was observed, but this is exceptional. On the other hand, it may often be clearly seen that the magnetite has, to a greater or less degree, been removed by solution; but in all such cases the place that it once occupied exists within the fringe of rutile, but is itself wholly free from the needles. This space is often filled with calcite, or some similar carbonate, in slightly radiating tufts.

All of these observations seem to point to a contemporary origin for both the magnetite and rutile from some preexisting mineral, which in the present case may very probably have been ilmenite.

The change of hematite into magnetite is one which has been often observed. Roth[1] quotes descriptions of this alteration from Breithaupt, Volger, Peters, vom Rath, Petersen, Döll, Grattarola, and Zeparovich. There seems to be no reason why the corresponding titaniferous compound, ilmenite, should not also pass over into magnetite with the separation of its titanium in the form which is most stable for the conditions then prevailing.

Rutile is well known to be widely distributed in microscopic crystals through schists which have resulted from the regional metamorphism of both sedimentary and eruptive rocks. It must therefore be a compound well in accord with the conditions producing metamorphism.

The common presence of rutile needles in diabase rocks which have been intensely altered by pressure, and its absence in their unaltered forms, in connection with the fact that the original ilmenite disappears in proportion as the rutile is developed, has inclined such eminent petrographers as Lossen and Rosenbusch to the supposition that the latter mineral has originated from an alteration of the former. This hypothesis has derived much support from observations made in many of the Lake Superior greenstone schists which are altered diabases. In case of the particular rock under discussion, it is impossible to prove with the material now in hand that the magnetite and associated rutile have resulted from preexisting ilmenite, but in light of all that we know of this and other occurrences, it seems to the writer that such an origin is, to say the least, not at all improbable. Whether or not such an alteration as that here suggested really takes place in the ilmenite of diabase when this rock undergoes dynamic metamorphism to chloritic schists must remain for future investigations to decide.

Nos. 4164 and 4165, from Prof. Irving's collection, show the same rock as the two specimens last described in a yet more advanced stage of alteration. Both have become typical chlorite schists, composed

[1] Allgemeine und chemische Geologie, vol. 1, 1879, p. 97.

mostly of chlorite, quartz, and iron hydroxide. The structure is now finely parallel and schistose, not the least trace of the original structure remaining. In No. 4165, which is the darker colored of the two, leaflets of a colorless mica (sericite) are abundant.

No. 11072, collected from Brooks's point *cc*, is a dark green rock, which is seen with the unaided eye to be traversed by numerous fibrous veins of a paler green color. Under the microscope the section of this rock shows principally ragged areas of green hornblende, inclosing isolated crystals of a mineral, which agrees more closely in its physical properties with zoisite than with any other; i. e., there are colorless rectangular sections with a cleavage parallel to the longest axis, and a cross-parting in the direction perpendicular to this. In polarized light these sections show pale, bluish gray interference colors, parallel extinction, and a biaxial figure. The fibrous veins, which compose a considerable proportion of the rock, are made up of zoisite individuals arranged perpendicular to the walls of the vein, and of fibrous hornblende, which often penetrates the former mineral in fine asbestiform needles.

THE LIGHT COLORED GREENSTONE AT UPPER QUINNESEC FALLS.

The speckled rock which forms the barrier at Upper Quinnesec Falls, is a very typical representative of the light colored greenstones of the Menominee region. It has a strong macroscopical resemblance to the rocks of this type already described from Sturgeon Falls and Lower Quinnesec Falls, but is more attractive in appearance than any of them. In the field it appears to be a medium grained aggregate of a white, opaque feldspar, in which, however, glistening, striated surfaces are by no means rare, and a grayish green mineral with a half metallic luster on its cleavage planes. The deceptive appearance of this mineral is the reason why Prof. Hermann Credner calls this rock (which he described as early as 1870) a diabase with a decided resemblance to a gabbro.[1]

This mineral does, indeed, show the most striking macroscopical similarity to the diallage of some of the Volpersdorf and Italian gabbros; but in spite of this fact, the most careful microscopical examination of many different specimens—the freshest that could be discovered—failed to disclose a trace of pyroxene. This result is the more surprising as the rock appears even fresher than that at Sturgeon Falls in which considerable pale diallage still remains. The microscope, however, shows that the rock at Upper Quinnesec Falls is the more altered of the two.

No. 11054, collected on the Wisconsin side of the river, directly at the fall, may be regarded as a typical specimen of the perfectly massive

[1] In speaking of this constituent he says: "Er [der Augit] bildet kurzsäulenförmige, zu krystallinischen Partien verwachsene Individuen, an denen orthodiagonale Spaltungsflächen mit halbmetallischem Glanze besonders deutlich hervortreten. Dadurch erhält das Gestein eine Aehnlichkeit mit Gabbro, selbst mit Hypersthenit." (Neues Jahrbuch für Mineral., 1870, p. 972.) Professor Pumpelly also says that this rock is identical with that of Sturgeon Falls. (Geol. Wisconsin, Vol. 3, p. 564.)

rock. Its microscopical appearance is represented in Plate X, fig. 1. The hornblende is mostly of a very pale color and more or less fibrous in structure. It has every appearance of being secondary, and yet in every case where it can be traced into a more compact mineral this is also a hornblende of a dark green or brown color. In many instances the hornblende is bent and curved, as diallage is so apt to be (see right side of the plate); but the most striking peculiarity of this hornblende and the one most like diallage is its very perfect parting, parallel to the orthopinacoid (100). This very unusual feature is apparently confined to the paler, and probably secondary hornblende. It stops abruptly on the edge of the compact, more deeply colored variety, even where this is continuous with the lighter kind (Plate X, fig. 1).[1] This may indicate that the paler hornblende is secondary after diallage and therefore reproduces its orthopinacoidal parting, while the diallage was itself intergrown with an original compact hornblende which still remains. Aside from its characteristic prismatic cleavage, proof is furnished that this mineral is really hornblende by the fact that sections approximately perpendicular to the vertical axis, give, in converged polarized light, a bisectrix instead of an optical axis.

The feldspar of this rock is largely changed to opaque, gray saussurite. Portions of it, however, remain in an unaltered state. These have, even in the thinest sections, a pale brown color (Pl. X, fig. 1), and in thicker sections they are as dark as mahogany. This coloring is not due to inclusions from which the feldspar is surprisingly free, but to some unevenly distributed pigment whose nature it is far beyond the power of the microscope to reveal. With the exception of this color the feldspar is so remarkably fresh and clear as to make the impression at first glance that it must be of secondary origin. A slight examination, however, shows that the clear brown substance forms a peripheral zone about the saussuritized individuals; or where the whole crystal is unchanged, that it is bent, broken, or faulted in a manner inconsistent with any supposition of secondary origin. Here again we have additional, and, indeed, most convincing evidence that the greater the mechanical action to which the feldspar has been subjected, the less chemical change it has undergone. (See above, p. 88.)

The other constituents of this rock are ilmenite, surrounded by a leucoxene border, and some secondary quartz, which is penetrated by most delicate fibers of hornblende.

The analysis of this rock in column I of the following table was made by Mr. R. B. Riggs:

[1] It is interesting to note, in this connection, the recent observation of Cathrein that the hornblende of Roda in the Tyrol has a perfectly developed parting due to very narrow twinning-lamellæ which run parallel to the orthopinacoid. (Zeitschr. für Kryst. u. Min., vol. 12, p. 12.) Whether the above-mentioned parting is due to the same cause or not, it is impossible, on account of the extreme narrowness of the parting-lines, to determine.

	I.	II.	III.
Silica (SiO_2)	48.35	51.46	47.96
Alumina (Al_2O_3)	15.40	14.35	16.85
Ferric oxide (Fe_2O_3)	4.04	3.90	4.33
Ferrous oxide (FeO)	4.63	5.28	4.17
Lime (CaO)	10.38	9.08	13.25
Magnesia (MgO)	11.61	9.54	9.15
Soda (Na_2O)	1.87	2.92	1.25
Potash (K_2O)	.35	.24	.30
Water (H_2O)	3.60	3.30	2.89
Carbon dioxide (CO_2)	.08	.20	.08
Total	100.31	100.27	100.23

Dried at 105°.

The analyses of the two analogous rocks, Nos. 11171 (II) from Sturgeon Falls, and 11008 (III), from Lower Quinnesec Falls, are again cited from, pp. 76 and 89, for comparison. The agreement between all three analyses is as close as could be expected for three different specimens of the same rockmass. In fact it is difficult to escape the conviction that the rocks from both Upper and Lower Quinnesec Falls, like that from Sturgeon Falls, were once diallage-plagioclase aggregates or gabbros; and yet if this be true, we are compelled to assume either that the original diallage passed by paramorphism into compact brown hornblende before reaching its present state; or that the original rock was a hornblende gabbro in which both bisilicate constituents passed finally into pale fibrous hornblende, although this process progressed much more slowly with the hornblende than with the pyroxene.

The feldspathic component of this rock (No. 11054) is determined by the analysis to be labradorite, as was also found to be the case in the corresponding specimens from the other localities.

Two other specimens of this same rock, No. 11061, from the Michigan side of the falls, and No. 11073, from a point above the falls, marked *p* on Major Brooks's map, are essentially the same as the one just described. Both are, however, more altered and both show, in a still greater degree, the effects of pressure upon the constituent minerals. In No. 11061 a good deal of quartz is present, always penetrated by delicate needles and tufts of hornblende. The largest areas of this quartz form a rather coarse grained mosaic and look as though they had been deposited as a pseudomorph after some former constituent. Some colorless chlorite is also present in this section, having been derived from the alteration of the hornblende. The feldspar of No. 11073 is colorless, and has been fissured, broken, and even crushed in a surprising manner. As a result, the saussuritization of this mineral has hardly more than commenced, in spite of the advanced state of alteration observable in the hornblende. One hornblende section in this slide, cut nearly perpendicular to the vertical axis, shows a very sharp line of demarcation between the interior, dark brown portion and the

colorless peripheral zone. This resembles somewhat the secondary hornblende enlargements recently described by Van Hise,[1] but I can not regard this particular case as due to anything but exterior bleaching.

Nos. 11056 and 11057, from the Wisconsin side of the fall, illustrate the passage of this pale diorite into schistose varieties, as described at Lower Quinnesec Falls. The former specimen, though macroscopically still quite massive, has lost the distinctness of its structure. Under the microscope this is seen to be due to crushing and attendant chemical changes. The feldspar is almost pulverized, but has otherwise undergone but little change. A few of the larger crystals have been merely cracked and faulted as shown in Fig. 11. The hornblende is very largely changed to a colorless chlorite. Where one of the hornblende crystals has been broken and sheared, chlorite is seen to have been developed in parallel fibers. This furnishes an admirable microscopic illustration of how the schistose bands are formed by pressure in the rock-mass as a whole. (See also Fig. 22, p. 128.) Just below the falls this rock becomes broken, gashed, and seamed with narrow, parallel veins of lamellar minerals. These gradually increase to bands, which finally compose the main portion of the rock. There can remain no doubt in the mind of anyone who will carefully study this exposure, that these schistose bands have been produced in the massive rock by the action of pressure, along lines where there has been a shearing motion.

FIG. 11.—Faulted feldspar crystal in crushed greenstone (No. 11056) from Upper Quinnesec Falls. Nicols crossed; magnified 30 diameters.

No. 11057 is from one of the schistose bands in No. 11056. The microscope shows it to be composed of a fine mosaic of quartz and feldspar (?) grains, made schistose by parallel fibers of serpentine and chlorite.

At and just below the engine house on the Michigan side of Upper Quinnesec Falls is another exposure which illustrates the gradual passage of these light colored, massive greenstones, into silvery, hydrous schists, similar to those described as occurring just below Lower Quinnesec Falls.

No. 11065 is a very light colored, although nearly massive, rock, seen in situ in a wall behind the engine house. It is composed of much crushed and faulted feldspar of the above described brown variety, together with colorless isotropic chlorite. There is also some of the quartz albite mosaic, though this is not abundantly developed, with a little iron oxide. There is no parallelism in the arrangement of the constituents which would tend to produce a schistose structure.

[1] Am. Jour. Sci., 3d series vol., 33, 1887, p. 385.

No. 11066 is from the same rock-wall as the last specimen and is undoubtedly continuous with it. It is decidedly schistose, and is composed wholly of a granular mosaic, with both sericite scales and a colorless chlorite. There are the finest microscopic rutile crystals in this rock that were encountered in any specimens from the Menominee region. These crystals are simple individuals, twins and trillings showing a great variety of form. A few are represented in the accompanying figure. They are grouped together or arranged in lines or strings which follow the direction of the schistosity. As in other similar instances before described from the Lower Falls, they appear to have originated from the alteration of the ilmenite of the massive rock.

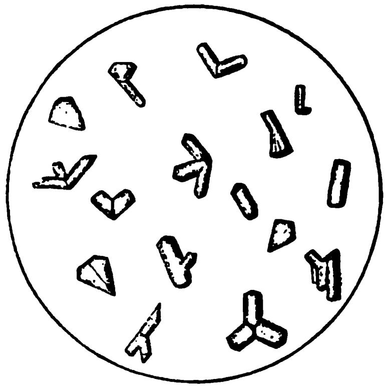


FIG. 12.—Rutile needles in No. 11036 magnified 350 diameters.

Just below the engine-house similar sericite schists are exposed (No. 11067 [1]) which contain green chlorite in spots and appear to grade into typical dark green-chlorite schists (No. 11068). These rocks are mentioned by Major Brooks at the exposures marked on his map *x* and *y* [2]. These dark green schists are like those which originate from the alteration of the dark colored diabases, and their appearance probably marks the commencement of the belt of these rocks which skirts the basin below the Falls.

THE COARSE GRAINED DIORITES OF THE HORSE RACE.

The half mile of comparatively quiet water, navigable by a small boat or canoe, immediately above the Upper Quinnesec Falls is bordered mostly by massive or schistose greenstones of the dark type similar in all respects to the rocks of this kind which have been studied at several other localities on the Menominee River. They are interspersed with bands of gneissose rock, identical with those yet to be described.

The narrow gorge known as the Horse Race, through which the river flows for a mile or more, has, however, been excavated through rocks of a quite different character. These are for the most part coarse grained diorites, penetrated by bands of granitic and gneissic rocks which will receive special consideration in the following section.

Typical specimens of these coarse grained diorites are Nos. 11077 and 11093 from the Wisconsin, and Nos. 11182, 11183, 11185, and 11186 from the Michigan side of the rapids.

The macroscopical appearance of these rocks is often that of an almost

[1] This rock was called by H. Credner "talc-schist" in 1869 (Zeitschr. Deutsch. geol. Gesell., vol. 21, p. 529). It was described in 1876 by Wichmann, who gives seven reasons for regarding the sericite schists as of fragmental origin. (Geol. Wisconsin, vol. 3, p. 638.)

[2] Ibid., 1, pp. 473, 474.

uniformly gray mass, in which the large and frequently glistening hornblende crystals are not at first glance very apparent. This color is due to the alteration of the feldspar, in which new minerals are largely developed. An opaque, white feldspar, or rather saussurite, is, however, often visible. This is sometimes in the form of rounded or oval areas which represent the centers of crystals that have turned gray around their edges; sometimes in the form of the original feldspar crystals themselves, and again in sharp contrast with the dark green hornblende. The grain of these rocks varies extremely, but is rarely fine. The form of the different constituents is always visible to the naked eye; and, in some instances (No. 11192), these measure from one to two inches in diameter.

Aside from the unusual coarseness of their grain, the rocks of the Horse Race differ from the other greenstones of the Menominee in frequently containing biotite. Another striking contrast is presented in the almost universal presence of talc. This mineral has without doubt originated from the hornblende, and has wandered from it into the feldspar. It is scattered everywhere through the rock in minute, silvery, glistening scales, and it coats all cracks and fissures. The surface of the hornblende crystals is also frequently spotted with it. The nature of this mineral as talc is easily determined by both optical and chemical means. Under the microscope it is of a pale green color, resembling muscovite in its cleavage and brilliant interference colors, but with a small optical angle and negative character. It is infusible and not attacked by acids, while microchemical tests show that it is destitute of both alumina and alkalies.

The structure of the Horse Race rocks is that of the second kind mentioned by Rosenbusch as occurring in diorite,[1] i. e., that conditioned by the feldspar having crystallized before the hornblende. The latter component is plainly allotrimorphic, like the pyroxene in diabase, while the feldspar has a well developed form of its own. (Pl. XII, fig. 2.) The hornblende, although comparatively compact and homogeneous over considerable areas, nevertheless conveys the impression of being of secondary origin. It has a pale green color, slightly darker toward the edge, and is externally frayed out into a fringe of radiating actinolite fibers, which wander along the cracks in the feldspar. (No. 11186; see Pl. XII, fig. 2.) In some sections—notably in No. 11185—large portions of the hornblende have become wholly changed to a felt-like network of minute fibers. These characters, together with the shape of the hornblende individuals, convey the impression that they have been derived from pyroxene. While, therefore, it is impossible to prove it with certainty, it is difficult to escape the conviction that these rocks were originally coarse grained gabbros or diabases.

The feldspar shows in almost every instance a broad twinning stria-

[1] Mikros. Physiog., 2d ed., vol. 2, p. 121.

tion, although this is more or less obscured by chemical changes. In one specimen (No. 11182) there is a brown feldspar which is perfectly preserved around the periphery of the crystals, while their interior is changed to saussurite. In other cases (Nos. 11093 and 11185) the feldspar is largely changed to saussurite, with which is mingled a good deal of actinolite and some biotite. In the latter case clear areas of brilliantly polarizing talc are quite abundant. In Nos. 11077 and 11186 the white or colorless feldspar is comparatively well preserved, but it is filled with pale green actinolite needles and some little biotite, which appear to have wandered into it from the hornblende. In these rocks the amount of saussurite is inconsiderable.

Brown biotite is not infrequently an important constituent of these rocks. It is especially abundant in No. 11077. Although sparingly scattered through the feldspar like the actinolite, it is mainly to be found in close association with the hornblende, with which or out of which it seems to have been developed by secondary processes.

Other specimens represent exceptional varieties of the Horse Race diorites.

No. 11091, from the Wisconsin bank of the stream, shows the feldspar wholly changed to a compact aggregate of epidote grains.[1] The hornblende, which is in sharp crystals, presents its usual appearance and characteristics. The epidote is so light colored that it might easily be mistaken at first glance for feldspar in the hand-specimen. The microscope, however, at once shows its true character. The interference colors of the closely interlocking grains present a brilliant appearance. No trace of the original feldspar remains. Only an occasional grain of calcite or quartz interrupts the continuity of the epidote. Epidote is not an unusual secondary product in feldspar, although such perfect pseudomorphs of this mineral as are here present are rare.[2]

Still other specimens show, in a marked degree, the effects of dynamic metamorphism upon the Horse Race rocks. No. 11189, from the head of the rapid, on the Michigan side, has a pronounced gneissic structure. Its hornblende is of the usual character, sometimes in compact crystalloids of large size, sometimes in a fibrous aggregate, but almost always much twisted, bent, or broken. The feldspar, in some instances, is completely changed to an aggregate of epidote crystals, as in the rock last described; in others, it merely has minute, highly refracting epidote grains more or less abundantly developed in it (saussuritization). These are often accompanied by rhombic dodecahedra of a colorless garnet.[3] Other of the feldspar individuals show a mechanical rather than a chemical alteration. There is, in some cases, a

[1] A not unusual alteration according to Roth; Allgemeine und chemische Geologie, vol. 1, 1879, p. 321.

[2] Cohen mentions such a perfect transformation of feldspar to epidote in the diorite which forms the base of the island Palma. Neues Jahrbuch für Mineral., 1876, p. 751. Rosenbusch also mentions them in diorites from the Vosges Mountains. Mikros. Physiog., 2d ed., vol. 2, p. 103.

[3] Rosenbusch: Mikros. Physiog., 2d ed., vol. 2, p. 136. Paul Michael finds one of the two varieties of saussurite in the gabbro of Wojaleite, Fichtelgebirge, composed of a lime-alumina garnet and serpentine. Neues Jahrbuch für Mineral., 1888, vol. 1, p. 39.

peripheral granulation (randliche kataklase) producing the "mortar structure" (Mörtel-Structur of Törnebohm). In other cases there is a complete reduction of the whole feldspar crystal to a granular mosaic, while in still others there is only a separation into large, interlocking, and but slightly disturbed areas. Fine veins of epidote not infrequently traverse these feldspar crystals. A point of mineralogical importance connected with this rock is the evidence it affords of the alteration of ilmenite into sphene. The usual alteration product of this mineral, leucoxene, is now generally believed to belong to this species, but it is rare to find the crystalline form of the sphene so typically developed as in this section. The mineral is of a grayish brown color and nearly opaque, like the secondary leucoxene which surrounds ilmenite. It polarizes with dull colors, but there is no mistaking its nature on account of its characteristic form. (Pl. XIII, fig. 1.)[1]

No. 11078, collected on the Wisconsin side of the river, just below the Horse Race, is perfectly continuous with No. 11077, above described, and represents a phase of this rock produced by the action of intense pressure. The hornblende is almost wholly changed to an aggregate of weakly polarizing fibers, which, according to the descriptions of Rosenbusch, are perhaps best regarded as of a serpentinous nature. These twine in and around the feldspar so as to produce a sort of "Flaser" structure. The feldspars themselves are sometimes reduced to a mosaic; but sometimes they have only a peripheral granulation. Much of the biotite of the unaltered rock remains among the alteration products of the hornblende. The iron ore has been drawn out into sinuous stringers which follow the direction of the foliation.

No. 11191 was taken from a wavy schistose, chloritic band on the Michigan side of the Horse Race. It has a strike 30° E. of N., and traverses a coarse grained massive greenstone, into which it passes by insensible gradations. In this rock there is considerable hornblende, which is seen in the process of transformation to a fibrous, yellow serpentine. The feldspar is of the reddish brown variety and has undergone granulation around the edge. This has been accompanied by the production of quartz and calcite. In a large area of the latter mineral there are crystals of a substance whose exact nature could not be determined. It has the bluish interference colors of zoisite, a parallel extinction and a biaxial interference figure. It is also changing to the same yellow serpentine as the hornblende. The sepentine penetrates and traverses it as it does crystals of olivine. Chlorite is also a frequent component of this rock.

Nos. 11080 and 11195 are exceptionally fine grained greenstones, the former from the foot and the latter from the head of the Horse Race. Both are composed essentially of actinolite, feldspar, quartz, and epidote, and resemble in their microscopical appearance and structure the

[1] Schenck observed the titanic iron entirely replaced by sphene in a schistose diabase from the upper Ruhr Valley. Inaugural Dissertation, Bonn, 1884, p. 57.

typical so-called "crystalline schists." Still the former is massive and cuts across the strike of schistose rocks like a dike, while the latter is decidedly schistose. No. 11195 contains minute and sharp, dark brown sphene crystals, which appear to have originated, like those in No. 11189, from the alteration of ilmenite.

THE ACID ROCKS OF UPPER QUINNESEC FALLS AND THE HORSE RACE.

Among the rocks to be found in the neighborhood of the Upper Quinnesec Falls and Horse Race are those of an acid type. They occur in bands of varying width, which generally, but not always, conform to the foliation of the greenstones. These acid rocks are sometimes massive granites without a trace of schistose structure; sometimes gneisses with a "Flaser" or "Augen" structure, and sometimes finely banded and schistose rocks like the Saxon granulites. Whenever these bands show any indications of schistose structure this seems to be conformable to the cleavage of the adjoining greenstones, without reference to what the direction of the band itself may be. Inasmuch, however, as these two directions *generally* coincide, it is not common that the foliation of the acid bands makes any angle with their sides. Such instances were nevertheless occasionally found, and they have a very important bearing on the genesis of these rocks and on their relation to the greenstones which surround them.

An inspection of the published geological maps of the region south of Lake Superior[1] will show that immediately south of the portion of the Menominee River under discussion there is an enormous area of a typical granite. Major Brooks, in his report on the Menominee district, thinks that this granite may very possibly be of eruptive origin, but, whether so or not, that it certainly overlies and penetrates ("in veins") the upper members of the greenstone series.[2] Since, however, he regards the greenstones as occupying the upper portion of the Huronian formation, he is compelled to assume that the granite represents its youngest member and hence he designates it as the "Huronian granite." (See profile, Fig. 2.)

Without entering in this place into a discussion of the stratigraphical relationships of these rocks, it may at least be stated with certainty that this granite does penetrate the greenstones in the form of dikes and apophyses, especially where the main mass approaches nearest to the river. This point is about half a mile south of the Horse Race, as may be seen by Major Brooks's section and map of this region[3]. Here the typical, coarse grained and somewhat porphyritic granite appears in a high ridge.

The adjacent greenstones and greenstone schists do not here materially differ from those at Upper Quinnesec Falls. They strike nearly east

[1] Geol. Wisconsin, vol. 3, atlas, Pl. XXVIII; Mon. U. S. Geol. Survey, vol. 5, Pl. I; Fifth Ann. Rept. U. S. Geol. Survey, Pl. XXII.
[2] Geol. Wisconsin, vol. 3, pp. 452, 531, 719.
[3] Ibid., Pl. III, p. 472.

and west and dip to the south. Near the granite contact they are filled with dikes of all sizes, evidently offshoots from the main granite mass (Nos. 11105 to 11107). These dikes, when small, are fine grained and felsitic, but when larger their texture is coarser and they have frequently a well developed schistose structure parallel to that of the adjoining schists. After a careful examination of this locality and of the exposures between it and the river, there is no doubt in the writer's mind that the granite, "Augengneiss," biotitic gneiss, and schistose porphyry (or "porphyroid," as Credner calls this rock) visible near the Upper Quinnesec Falls and along the Horse Race, are also dikes or aphophyses connected with the main southern granite area. The schistose or banded structure of these rocks, when such exists, is a secondary feature, produced by the same dynamic agencies which rendered the greenstones themselves schistose.

An intelligent study of these acid rocks should begin with an examination of the massive granite from the large area south of the Menominee. No. 11104 was collected near the contact, about half a mile south of the Horse Race, where, after appearing in numerous dikes in the greenstone, the solid mass of granite appears in an abrupt wall, trending N. 80° E. This rock appears in a hand-specimen to be a typical, coarse grained granitite, with a decided tendency to a porphyritic structure. The latter feature may, however, be due to the nearness of this locality to the contact. When examined under the microscope, the macroscopic diagnosis is found to be correct and several additional points of interest are brought to light. The oldest constituents are zircon and apatite; both quite abundant in the form usual in granitic rocks. Iron oxide seems to be almost absent as an original constituent, though it is found in some of the altered micas. The biotite, the only mica present, is not abundant. It is invariably bleached to a green color by the reduction of its iron to the ferrous state. It contains abundant inclusions of apatite, zircon (around which are pleochroic aureoles), and some secondary magnetite. No trace of either hornblende or pyroxene was observed. Sphene, however, is present, as are also a few sharp crystals of a dark grayish blue tourmaline. The principal interest of this rock attaches to its feldspar and quartz. They together make up nearly the whole mass and exhibit, in a remarkable degree, the effects of pressure. The feldspar is of three kinds: normal plagioclase (oligoclase), unstriated orthoclase, and microcline. The relationship of these species of feldspar is a suggestive one. Both the oligoclase and the orthoclase are always altered to a fine micaceous or kaolinitic product which is particularly abundant in the center of the crystals, a zone of the unaltered mineral being often preserved around the edge. The microcline, on the other hand, almost never shows any indication of alteration.

It is always clear and fresh in appearance, but its twinning lamellæ are bent or curved and bear every sign of having been secondarily developed.[1] In other words, we have here again, in the writer's opinion,

[1] Rosenbusch, Mikros. Physiog., 2d ed., vol. 2, p. 295.

a striking example of the mechanical action apparent in the feldspar, being inversely proportional to the chemical action which has gone on in it. Original orthoclase has been converted partly into kaolin, partly into microcline, according to the way in which the action of the force manifested itself. The effect of the force which acted upon this rock is also apparent in other ways. The large original feldspar crystals show a peripheral granulation (see Chapter I, p. 49), and where they have been fissured their cracks are filled with a new crystallization of plagioclase, orthoclase, and quartz. None of these minerals shows any signs of chemical alteration and microcline is never to be found among them. Thus is produced a good example of what Törnebohm has called a mortar structure ("Mörtel-Structur")[1]. In this secondary cement-like aggregate, a micropegmatitic intergrowth of quartz and feldspar is quite common, and calcite, in good-sized individuals, is by no means rare.

The original quartz of this granite also shows many indications of having been squeezed. The crystals or grains often have an undulatory extinction, while larger grains are broken and the fragments are more or less displaced. Proof that these were not originally different grains is given in section No. 11104, where a small tourmaline crystal is broken and faulted just at the contact.[2] (See Fig. 13). No. 11105 is a specimen of the prevailing rock near the granite contact. This is a hornblende schist, composed mainly of irregular grains of dark green hornblende and quartz. There are beside some striated and some unstriated feldspars, a little sphene and an abundance of extremely sharp and clear epidote crystals. The banding of this rock is caused by the preponderance of hornblende in some layers and of quartz in others. Its strike is nearly east and west and its dip 75° to 80° to the south. Under the microscope all of the constituents by their extreme freshness and freedom from all inclusions convey the impression of being secondary crystallizations. The texture of the rock is granular, although the epidote is present either in exceedingly sharp crystals (which often pass unbroken from one quartz grain into another) or in much more minute, ovoid granules, forming the little, highly refracting particles which are so common in the crystalline schists. No. 11107 was taken from one of the wider of the numerous acid dikes which pene-

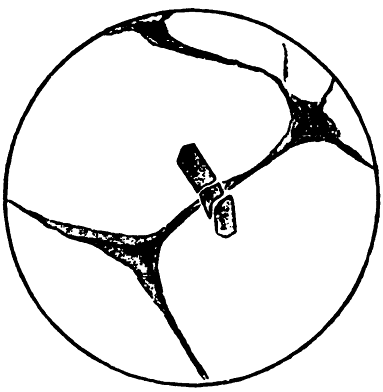


FIG. 13.—Broken tourmaline crystal proving the secondary fracture of the inclosing quartz grain, "Horse Race" granite. No. 11104.

[1] Några ord om granit och gneis. Geol. Fören. Stockholm Förhandl., 1880-'81, vol. 5, p. 233, (ref. Neues Jahrbuch für Mineral., 1881, vol. 2, Referate, p. 51; and Rosenbusch, Mikros. Physiog., 2d ed., vol. 2, p. 42.)

[2] Compare Dr. Chelius's remarks on the Hessian granite-porphyries, Notizblatt des Vereins für Erdkunde zu Darmstadt, 1883.

trate the last described hornblende schist in the neighborhood of the granite contact. It has a decidedly gneissic structure parallel to the banding of the inclosing schist, which is here also the direction of this band or dike. The microscope shows that the mineral composition of this rock is identical with that of the coarse granite (No. 11104). There is the same zircon, sphene, and tourmaline associated with the biotite, feldspar, and quartz. The differences are the gneissic structure, fineness of grain and absence of all porphyritic structure in the dike rock, while none of its constituent minerals show the chemical alteration which has progressed so far in the massive granite. Both the biotite and the feldspar are quite fresh, the rich brown color of the former contrasting with green and bleached mica above described.

After the foregoing review of the character of the acid rocks at and near the granite contact, we are in a much better condition to understand the occurrence of the bands of gneiss and porphyroid near the Upper Quinnesec Falls, which were observed by Major Brooks and Prof. Pumpelly.[1] If we now examine some of the most typical of these exposures with care, we shall find that they are quite identical with the rocks which we have just been considering.

On the lower side of a small cove which indents the Wisconsin river bank immediately below the Horse Race there is a narrow band of acid rock well exposed on the shore. The center of this band is composed of a massive, gray colored, porphyritic rock resembling a granite (No. 11082). This grades on both sides imperceptibly into a well characterized, fine grained gneiss (No. 11085), which in places is so finely banded as to resemble some of the Saxon granulites (No. 11084). The foliation of this exposure is nearly vertical and seems to be quite parallel to the sides of the band, which itself makes only a slight angle with the cleavage of the adjoining greenstones.

No. 11082 was collected from the central and most massive portion of this acid band. Macroscopically the rock appears to be a typical granite porphyry, nor does the examination of a thin section with the microscope reveal anything opposed to this determination. The following analysis of the rock, however, made by Mr. R. B. Riggs, shows that this rock is in reality a diorite:

Silica (SiO_2)	54.83
Alumina (Al_2O_3)	25.49
Ferric oxide (Fe_2O_3)	1.61
Ferrous oxide (FeO)	1.65
Lime (CaO)	6.08
Magnesia (MgO)	1.96
Soda (Na_2O)	5.69
Potash (K_2O)	1.87
Water (H_2O)	1.18
Carbon dioxide (CO_2)	.18
Total	100.54

[1] Geol. Wisconsin, vol. 3, p. 474.

The microscope discloses good-sized crystals of a striated and zonally formed feldspar embedded in a granular mosaic of clear, colorless, and unstriated grains associated with brown leaflet of biotite. Apatite, zircon, and a reddish pleochroic sphene are also present in small crystals. In spite of this rock showing no indication whatever of alteration, it contains calcite in considerable quantity. This mineral apparently penetrates and includes all the other constituents in a manner which has led Hawes,[1] Törnebohm,[2] and Chrustschoff,[3] to regard it under similar circumstances as a product of the original crystallization. In one section of the present rock sharply defined sphene crystals were observed wholly surrounded by the calcite. Nevertheless the presence of this carbonate in the fresh rock is to be explained, as Rosenbusch suggests, by the filling up of drusy or miarolitic cavities.[4]

The rock appears both macroscopically and microscopically to be a granite porphyry with a microgranitic groundmass. The analysis, however, shows it to be largely composed of a feldspar of the andesine series, and this is also indicated by a further examination. The colorless grains of the groundmass, in spite of their limpid character and superficial resemblance to quartz, give in converged polarized light the brush or hyperbola of a biaxial crystal. In the Thoulet solution the colorless portion of the powder fell between 2.683 and 2.650, a large proportion, however, being confined between the limits 2.668 and 2.659. A small proportion possessed exactly the specific gravity of quartz, so that it is impossible to say with certainty whether this mineral is present in the groundmass. The relative proportions of silica and alumina, however, as given by the analysis, make this improbable. We must describe this rock as a very pure type of a mica-diorite porphyry whose groundmass is composed of a mosaic of clear unstriated lime-soda feldspar, probably andesine.

The two specimens (Nos. 11084 and 11085), taken from the gneissic portion of this exposure, when seen under the microscope, closely resemble the groundmass of the diorite porphyry just described. The chief difference is in the banded appearance, produced by the parallel arrangement of the grains, and especially of the mica plates. This is most pronounced in No. 11084, where the mica is collected in certain layers and where there is also an alternation in the grain, some layers being coarser and others finer. Occasional tourmaline crystals are here associated with the zircon and apatite. Calcite also is present, as in the last described rock, but now it is in stringers and arranged, like all the other components, in the direction of the schistosity. No. 11085 has neither the calcite nor the tourmaline. Its most interesting feature is the presence of long strings of minute rutile crystals which appear to

[1] Geology of New Hampshire, vol. 3, Part IV: Mineralogy and Lithology, 1878, p. 268, Pl. XII, Fig. 1.

[2] Om Kalkgranit. Geol. Fören Stockholm Förhandl., vol. 3, 1876, p. 210. Om Kalcithalt i graniter, Kong. Vetensk. ak. Förhandl., vol. 5, 1881, p. 233.

[3] Bull. Soc. Minéral. de France, vol. 8, 1885, p. 137.

[4] Mikros. Physiog., 2d ed., vol. 2, 1885, p. 34.

have originated from the alteration of the biotite. No. 11079, collected from a narrow acid band slightly east of this exposure, is quite identical in both composition and structure with the two last mentioned rocks. There are here occasional remains of former porphyritic feldspar crystals which have been mostly destroyed by granulation. Tourmaline is quite abundant, as are also flakes of colorless but brightly polarizing sericite.

It will be seen that these rocks are quite the same as those found farther south at the granite contact. Along the whole extent of the Horse Race similar acid rocks are very abundant. They occur in bands varying from the finest seams to such as are many yards in width. While these as a rule follow the direction of the foliation of the greenstones, they by no means always do so. Their mode of occurrence often bears strong testimony to their intrusive nature, as may be seen from the following figures sketched at the head of the Horse Race on the Michigan side of the river.

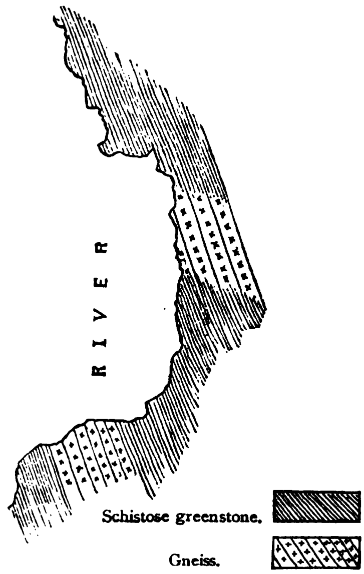


Fig. 14.—Exposure on the edge of a small cove at the head of the Horse Race. Direction of the shading lines indicates the strike.

Fig. 14 shows two bands of gneiss, one parallel to the strike of the greenstones, the other cutting across it. In each the lamination of the acid rock coincides with that of the greenstones, without regard to the sides of the band. This would seem conclusive evidence of the secondary nature of the gneissic structure.

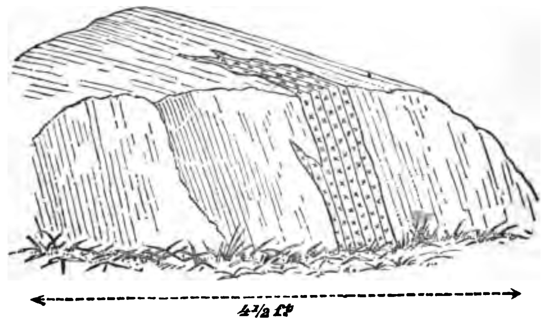


Fig. 15.—Foliated granite (gneiss) intrusive in greenstone. Head of the Horse Race.

Fig. 15 shows a band of gneiss which comes to an abrupt termination in the greenstone and which sends out apophyses into this, as only an intrusive dike would do.

Fig. 16 shows an irregular area of gneiss penetrating the greenstone. The lines in the drawing indicate the direction of the foliation. This may be a cross-section of a laterally intrusive arm.

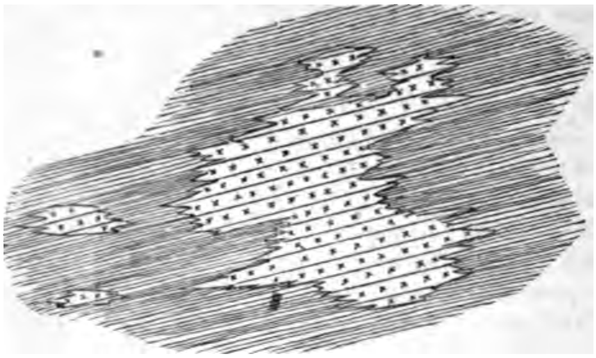


FIG. 16.—Foliated granite (gneiss) intrusive in greenstone. Head of the Horse Race.

Many other exposures might be selected to prove the intrusive nature of these acid rocks at the Upper Quinnesec Falls, but the ones already cited will suffice for the present purpose.

With respect to their structure, the acid rocks of the Upper Quinnesec Falls and Horse Race may be classified as follows:

I. Porphyritic:

Granite porphyry, represented by Nos. 11104, 11082, 11087, 11089, 11190.

Augen-Gneiss, represented by Nos. 11184, 11193 11196.

Schistose porphyry, represented by Nos. 11050, 11051, 11052, 11096.

II. Non-porphyritic:

Gneiss, represented by Nos. 11079, 11084, 11085, 11188.

Felsite, represented by No. 11071.

The main points of interest will now be stated with reference to each of these types in succession, although no further mention will be made of those specimens which have already been described, viz, Nos. 11104, 11082, 11084, 11085, 11079.

It is believed that the distinctive features of the schistose and banded rocks of this region have to a great extent been produced by secondary causes. An original porphyritic structure seems to have been very prevalent, if not universal, in all of these acid dikes. We are able to trace its gradual disappearance, and we find that this is proportional to the intensity of the dynamic action to which the particular rock has been subjected. The crushing or rubbing of the constituent minerals against one another has produced a peripheral granulation ("randliche Kataklase"). This has altered the porphyritic crystals into the eyes or "Augen" of the gneisses and schistose porphyries, as is shown in Pl. XV, fig. 1; and there seems no reason why its extreme application may not have changed a porphyritic rock to a felsite.

Granite porphyry.—No. 11190, from the Michigan side of the Horse Race, near its center, is from a small area of acid rock exposed at the water's edge, which seems to be completely surrounded on the three other sides by diorite. It is porphyritic, but contains a very large proportion of feldspars (mostly striated) and comparatively little groundmass. This latter is so arranged as to produce a resemblance to the *mortar-structure*, and thus the rock approaches No. 11104, although all of its quartz is confined to the groundmass. Biotite is quite abundant. It contains fine pleochroic aureoles, and is frequently bleached to a pale green color.

Nos. 11087 and 11089, both from the Wisconsin bank of the Horse Race, are decidedly porphyritic. A fine grained granular groundmass is in sharp contrast to the well formed feldspar crystals. These are noticeable on account of their finely developed zonal structure, which is produced sometimes by a concentric arrangement of inclusions, sometimes by a variation of composition and extinction angles in different layers. The zonal structure of the feldspars in these rocks is as perfect as it is in the more modern andesites. The mica in No. 11087 is biotite of the usual character, but in No. 11089 muscovite is equally abundant, making this latter rock a true granite instead of a granitite. Some of this muscovite, at least, may be plainly seen to have originated from the alteration of the orthoclase. In many cases it lies in brilliantly polarizing flakes of considerable size, clustered together in the center of the orthoclase crystals, which portion always appears to be the most subject to alteration.

These rocks show to a moderate degree the effects of pressure which are most manifest in the porphyritic quartzes. These are much distorted and often broken and granulated, as shown in Pl. XV, fig. 2. It seems at first thought strange that the harder quartz should be more susceptible to pressure than the softer feldspar, and yet this is known to be a well established fact, as has been observed in Chapter I. The brittleness of the quartz causes it to break, where the feldspar is only bent or distorted, without rupture.

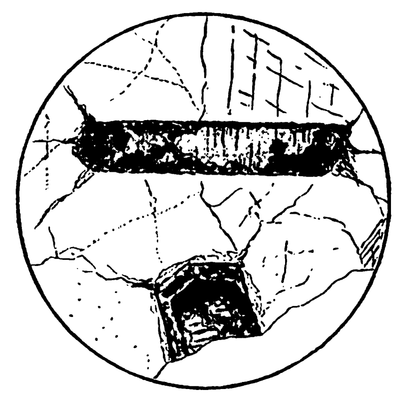


FIG. 17.—Orthite in granite. Horse Race Rapid. No. 11087. Magnified 80 diameters.

In some cases the feldspar, as well as the quartz, shows a slight peripheral granulation and passage into a mosaic, which can not be distinguished from the groundmass. This is in all instances, however, only incipient, while the main portion of the groundmass is an original feature of the rock.

In the granitites, Nos. 11087 and 11190 an unusual constituent is present. This is in sharp crystals of good size (2 by 3^{mm}) and has the shape of epidote. Its color is yellowish brown or greenish yellow.

It seems to have undergone partial alteration, and agrees closely with the published descriptions of orthite (allanite).[1] The two crystals in section No. 11087, although by no means entirely changed, appear to be completely isotropic, a peculiarity especially mentioned by Rosenbusch as not uncommon to orthite.[2]

Augen-Gneiss.—The best example of this type is No. 11184, from the Michigan side of the Horse Race. With reference to this rock the following is extracted from the field notes made in July, 1885:

A short distance above the mouth of the Horse Race the ridge is cut by a ravine. Here, near the water's edge, are some beautifully porphyritic, red, acid rocks, occurring apparently as dikes in the greenstone. The direction of these dikes is quite irregular. Their width also varies continually. They contain a deep red feldspar, a white feldspar, and quartz in porphyritic crystals. When much of the first mentioned feldspar is present, the rock is very red; when it is absent it is gray. Both varieties may occur in the same specimen. These rocks show the effects of pressure very finely. The porphyritic crystals form "Augen," around which the groundmass bends. The direction of the banding when well marked appears to be parallel to the walls of the dikes. The "Augen" stand vertically.

Under the microscope the banded or gneissic structure of this rock is as well marked by the lenticular ("Flaser") arrangement of the mica as in the hand-specimen. Its most instructive feature is the formation of the eyes ("Augen") and the gradual disappearance of the large porphyritic feldspar crystals by peripheral granulation due to pressure. A typical example of this is represented in Pl. XV, fig. 1. Here it will be seen that a large porphyritic crystal of triclinic feldspar has been granulated on two opposite sides, corresponding to the direction of the schistosity, and that the material thus formed has been drawn out into a lenticular-shaped mass, with the remaining solid portion of the feldspar as its center. This forms the eye or "Auge" around which the groundmass is seen to curve. Such a structure has been described and figured by J. Lehmann[3] and others. It is important to observe that the secondary granulation has here produced a mosaic of *much coarser grain* than the surrounding groundmass. This corresponds to observations of Dr. Chelius, made on certain Hessian granite porphyries.[4]

No. 11196, from the head of the Horse Race, on the Michigan side, is described in the field notes as "a typical biotite gneiss with a wavy structure, the biotite lamellæ (secondary?) winding around the porphyritic crystals of feldspar and quartz." Under the microscope the groundmass is seen to be fine grained, and, to some extent at least, to have originated from the granulation of the porphyritic crystals, which exhibit this process in an admirable manner. Dark brown biotite and sphene are common. Zircon and apatite are also present. The quartz

[1] A. Sjögren, Geol. Fören. Stockholm Förhandl., vol. 3, 1876, p. 258, Törnebohm Under Vega-Expeditionen insamlade bergarter. Vega-Exped. vetensk. jakttagelser, VI, Stockholm, 1884, p. 124. Cross & Iddings, Am. Jour. Sci., 3d series, vol. 30, 1885, p. 108.

[2] Mikros. Physiog., 2d ed., vol. 1, p. 499.

[3] Untersuchungen über die Entstehung der altkrystallinischen Schiefergesteine. Bonn, 1884.

[4] Notizblatt des Vereins für Erdkunde zu Darmstadt, 4. Folge, 5 Heft., 1885, quoted by Rosenbusch, Mikros. Physiog., 2d ed., vol. 2, p. 294.

is in large granular areas. Rows of fluid cavities traverse the grains and pass uninterruptedly from one to another.

The following analysis of this rock is also by Mr. R. B. Riggs:

Silica (SiO_2)	67.77
Alumina (Al_2O_3)	16.61
Ferric oxide (Fe_2O_3)	2.06
Ferrous oxide (FeO)	1.96
Lime (CaO)	1.87
Magnesia (MgO)	1.26
Soda (Na_2O)	4.35
Potash (K_2O)	2.35
Water (H_2O)	1.69
Carbon dioxide (CO_2)	.19
Total	100.11

This is much more like the analysis of a granitite than the last one given (No. 11082), but the preponderance of soda over potash indicates the presence of a large amount of soda orthoclase.

Schistose Porphyries or Porphyroids.—Just below Upper Quinnesec Falls, especially on the Wisconsin side, are good exposures of finely schistose acid rocks. They contain small porphyritic crystals of feldspar and quartz, and a considerable amount of sericite or hydro-mica, which winds around these crystals so as to produce a lenticular or "Flaser" structure. In color they present every shade from flesh red to gray.

Rocks of this general type have a wide distribution and have arrested the particular attention of petrographical investigators. In some instances they have been conclusively shown to be the product of the metamorphism of fragmental rocks—either tuffs or true sediments—while in other cases they have resulted from the action of great dynamic forces upon massive rocks of a corresponding composition, i. e. quartz porphyries. When it is possible to trace with certainty the origin of these rocks to stratified deposits they are usually designated as *porphyroids*, while in case their mother-rock can be shown to have been quartz porphyry they are usually called *schistose porphyries*. In their extreme development these two types are often petrographically indistinguishable and they present an instructive instance of the production of identical results by the action of the same physical forces upon matter of the same average composition, though differing widely in origin and its structure.[1]

The schistose porphyries occurring at Upper Quinnesec Falls were made the subject of an extended paper by Hermann Credner, published in 1870.[2] This author concludes from a macroscopical examination that these rocks are altered sediments which are interpolated between the

[1] Bull. U. S. Geol. Survey, No. 28, p. 1.

[2] Ueber Nordamerikanische Schieferporphyroide. Neues Jahrbuch für Mineral., 1870, pp. 970–984.

diabase beds of the Upper Huronian. He divides their whole exposure at this locality, which he gives as 300 feet, as follows:

	Feet.
(b) Weakly schistose orthoclase porphyroid	50
(c) Typical feldspar-paragonite schist	10
(d) Light flesh-red orthoclase-paragonite schist	30
(e) Paragonite schist	15
(f) Lime-paragonite schist	15
(g) Light reddish gray schistose porphyroid	30
(h) Lime-chlorite schist	50
(i) Chlorite schist	100
Total	300

Of (b), (c), (d), and (e) he gives the following analyses:

	(b)	(c)	(d)	(e)
SiO_2	66.70	72.45	76.505	75.5
Al_2O_3	15.90	8.85	7.950	8.6
Fe_2O_3	4.70	6.20	8.875	2.6
MnO	tr.	tr.	tr.	
CaO	tr.	tr.	0.322	7.2
MgO			tr.	1.2
K_2O	8.06	9.24	1.025	0.3
Na_2O	5.50	3.70	4.384	3.0
H_2O				1.5
Total	100.86	100.44	99.061	99.9

In discussing these analyses Credner finds sufficient proof that orthoclase alone is present, from the fact that the potash increases proportionately with the amount of feldspar, and in the absence of a twinning striation which is visible to the naked eye. The sodium he attributes entirely to the mica, which, in consequence, he names paragonite. The proof of sedimentary origin he finds in the constant parallelism of the schist planes with the limit between these rocks and the adjoining diabase; and yet he cannot help being much struck with the alternation of such widely diverse rocks in a single and comparatively thin complex.[1]

My studies of these rocks, both in the field and in the laboratory, have led me to results quite the reverse of those obtained by Credner. Nos. 11050 to 11053 were collected from the most typical band, which here stands nearly vertical and strikes 20° S. of E. They are all essentially the same in everything except color. They contain more or less rounded porphyritic crystals of quartz and a red or grayish feldspar, imbedded in a matrix apparently composed of a yellowish gray, greasy-feeling hydro-mica.

[1] Die ebenerwähnte Wechsellagerung vollkommen verschiedenartiger Gesteine als zusammengehörige Glieder einer wenig mächtigen Schichtenreihe ist höchst auffällig. Zwischen zwei Lagern von Diabas, also einem namentlich aus Kalkfeldspath und Augit bestehenden basischen Gesteine mit etwa 54 Proc. Kieselsäure tritt zunächst eine Zone von sauren quarzreichen Kalifeldspath-Natronglimmer-Porphyroiden mit über 70 Proc. Kieselsäure, aber ohne Kalkgehalt auf," etc.—Loc. cit., p. 981.

The following analysis of No. 11050 by Mr. R. B. Riggs shows its essential identity with Credner's specimen (b). Almost the only difference is the smaller amount of alkali, although the relative proportions remain about the same. In Credner's analysis the CaO and MgO, which make up this difference, do not appear to have been determined.

Silica (SiO_2)	66.69
Alumina (Al_2O_3)	16.69
Ferric oxide (Fe_2O_3)	2.06
Ferrous oxide (FeO)	.93
Lime (CaO)	1.40
Magnesia (MgO)	1.15
Soda (Na_2O)	2.46
Potash (K_2O)	5.23
Water (H_2O)	1.70
Carbon dioxide (CO_2)	1.42
Total	99.73

This is evidently the analysis of an orthoclase rock, and yet the microscope shows that a considerable proportion of the porphyritic feldspars are striated and triclinic, in spite of the fact observed by Credner, that this character is not apparent to the unaided eye. We may therefore reasonably suppose that the potash exists largely in the groundmass and in the secondary hydro-mica, which is to be regarded as true sericite, and not paragonite as assumed by Credner.

The microscope discloses in all the thin sections of these rocks the typical structure of a quartz porphyry modified, however, by the action of great pressure. An idea of it may be obtained from Pl. XIV, fig. 1, which represents No. 11050. The fine grained, microgranitic groundmass is still present, inclosing the porphyritic quartzes and feldspars. The former often exhibit their characteristic dihexahedral form, but they are broken and possess an undulatory extinction. The feldspars are most instructive. They possess a sharply defined crystal form which, however, has been cracked and the fragments have been more or less separated in the direction of the schistosity, while brightly polarizing sericite scales have been abundantly developed in all the fissures. Sericite is also abundant in the groundmass, where it appears to have been formed from the orthoclase. Its scales are parallel throughout the rock, to which fact the schistose structure is almost wholly due. The original biotite of these rocks is now entirely represented by a pale green chlorite. During the process of this alteration, iron has separated in the form of opaque, black grains; and, in some instances (11050 and 11052), colorless but very highly refractive grains have been produced. These sometimes possess a sharp octahedral form and are probably anatase, formed from the titanic acid of the original biotite, as described by Stelzner.[1] In and around this chlorite, tourmaline is also abundant either in single individuals or in groups of crystals. Zircon and apatite are sparingly present. One

[1] Neues Jahrbuch für Mineral., 1884., vol. 1, p. 273.

remarkably large (.4 × .04^{mm}) crystal of the former mineral, which has been curiously broken, is represented in Fig. 18, taken from No. 11052.

FIG. 18.—Broken zircon crystal in schistose porphyry. Upper Quinnesec Falls. No. 11052. Magnified 180 diameters.

Calcite is not uncommon and is always of a secondary nature. In Nos. 11051 and 11053 it forms a more or less complete border around the porphyritic crystals.

As already stated, all four specimens collected from this locality are essentially identical. No. 11053 is more finely schistose, owing to its more advanced stage of alteration and the consequent greater production of sericite. In spite of this, however, the original structure is still plainly visible. No. 11096 was obtained on the Michigan side of the river, at the foot of the Horse Race. It has a very pronounced schistose structure, and, under the microscope, appears nearly identical with the rocks just described from below the falls, but is not so highly altered. Its biotite is in its original fresh state, its porphyritic crystals are more intact, and sericite is not so abundantly developed.

Gneiss.—In addition to the nonporphyritic gneisses already described, Nos. 11079, 11084, and 11085 (see pp. 114–115) one other may be mentioned, No. 11188, from the head of the Horse Race, on the Michigan side. This is apparently a typical biotite gneiss, but it is seen to pass by gradual transitions into the hornblende gneiss No. 11189 (see p. 108). The microscope shows that there are many points of resemblance between these two rocks. In the present case, although quartz is abundant, amphibole and the same sphene observed in No. 11189 are frequent, and the feldspar is of such a nature as to be subject to saussuritization.

Felsite.—True nonporphyritic felsite is not common among the acid rocks of the area about the Upper Quinnesec Fall and the Horse Race. The most typical specimen of this class is No. 11071, which occurs in narrow bands in the schistose greenstones below the falls on the Michigan side of the river. This is a very compact, flesh colored rock resembling jasper. Under the microscope it is seen to be essentially identical with the groundmass of the porphyritic rocks above described; and even here stretched and distorted crystals of quartz and feldspar are not entirely wanting, though they are rare.

There is, therefore, strong evidence in favor of the view that the acid rocks of the Upper Quinnesec region are of eruptive origin; that they are to be regarded as apophyses which diverged from the granitic mass to the south; and that their schistose structure, when present, is to be attributed to secondary causes.

This evidence may be summarized as follows:

First. The structure of these rocks, as revealed by the microscope, in spite of its frequently being disguised by the action of secondary causes, is always that recognized as characteristic of massive or igneous rocks.

Second. There are present in these gneissoid bands granitic facies which agree exactly with the rock of the main granite area, and the bands themselves are identical with others near the contact, which can be plainly seen to be radiating apophyses or dikes.

Third. The schistosity of these bands is often independent of their direction and agrees with the prevailing strike of the surrounding greenstones.

Fourth. There is abundant microscopic evidence that the constituents have been fractured, stretched, and crushed since their solidifiation.

The localities thus far considered on the Menominee River, viz: Sturgeon, Lower and Upper Quinnesec Falls, contain all the important exposures of crystalline rocks, belonging to what Major Brooks has regarded as the southern of the two belts of greenstone. If his location of these rocks is correct, the members of the northern belt appear upon the river at three points, viz: Four-foot Falls, Lower Twin, and Upper Twin Falls, of which, however, the two latter are connected by almost continuous rock exposures. These localities we shall now proceed to consider in detail.

FOUR-FOOT FALLS.

The exposures at this place are represented, together with those at both the Twin Falls, upon Major Brooks's map, which is here reproduced in Pl. VI. The fall is hardly entitled to be so called, as the rocks have formed nothing more than a rapid in the river. Just at the foot of this rapid the river is crossed by the Chicago and Northwestern Railroad bridge, immediately beyond which a cutting has disclosed some very instructive exposures of the greenstones. The rocks may be seen in position on either side of the river for some distance above the bridge. Brooks distinguishes upon his map many alternating beds of massive, schistose, and slaty rocks (*a* to *n* in his section). The beds here strike about S 80° E—nearly at right angles to the direction of the river at this point—and yet are mostly schistose on the Wisconsin side and massive on the Michigan side. This fact is indicated on Major Brooks's map and speaks strongly against the view that the present foliation is due to original bedding.

The rock of the exposure which occurs farthest down the river (Brooks's *a*) outcrops somewhat less than a quarter of a mile below the bridge. It was called by Wright a chloritic slate,[1] and by Wich-

[1] Geol. Wisconsin, vol. 3, p. 712.

mann a phyllite. Major Brooks himself designates it as a "light bluish gray, shining *clay slate*, with strong cleavage and no distinguishable bedding planes."[1] It does not belong to the rocks now especially under consideration, but since it was studied carefully it may be described here for comparison. This slate occurs in a bed, estimated by Brooks to be 550 feet in thickness, on both sides of the river and in its bed. It strikes nearly east and west and dips toward the north. In Brooks's collection this rock bore the number 2075; in the present collection it is represented by No. 11152.

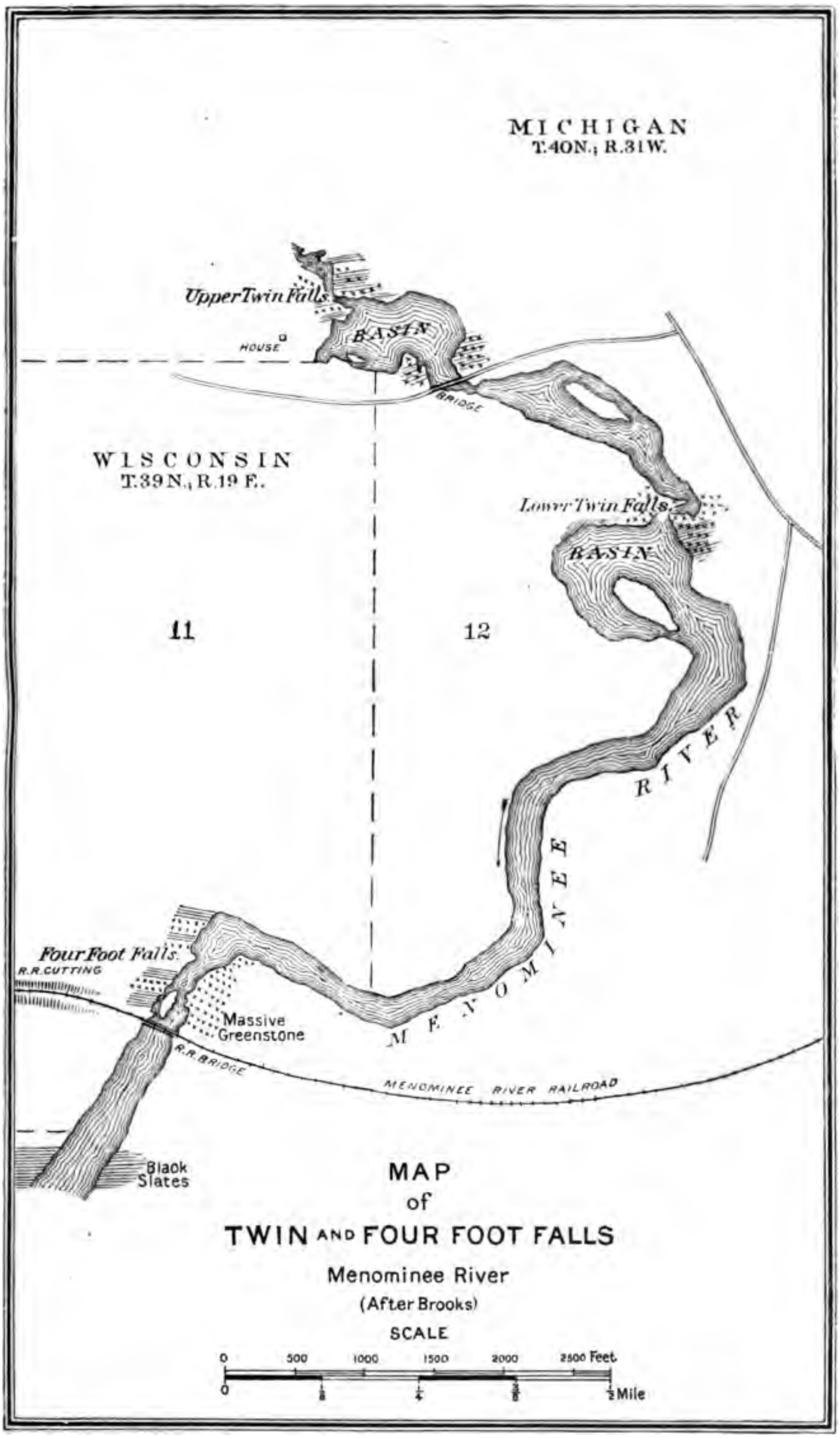
Under the microscope there are visible in the thin section of this specimen unmistakable signs of sedimentary origin. Coarser and finer areas alternate, the former being made up of clastic quartz grains, either pure or mixed with iron hydroxide or chlorite, while the latter are composed of an argillaceous substance, filled with extremely minute muscovite or sericite scales and considerable carbonaceous matter. Tourmaline needles are also occasionally seen; and zircon too, either in minute, whole crystals or as irregular fragments of larger ones, is not infrequent. This rock belongs to the detrital iron-bearing series, the boundary between which and the greenstone schists lies just above this exposure.

The railroad which crosses the bridge at Four-foot Falls exposes this same rock again in a cutting about a mile west of Iron Mountain. A specimen from this locality, No. 11114, shows the same general character as the last described rock, except that it is more crystalline. Tourmaline is present as before, but a new crystallization of biotite has largely replaced the chlorite. The carbonaceous material is less abundant and what remains is in a much more finely divided state. The clastic origin of the rock is still very apparent in the shape of its quartz grains, which are here mingled with feldspar fragments, both plagioclase, microcline and orthoclase.

No. 11113, from a quartzite band intercalated in No. 11114, also contains feldspar grains mingled with the quartz. Zircon fragments are likewise present and a little biotite, which is no longer quite fresh. This latter mineral shows in a beautiful manner the development of secondary rutile needles, as in the kersantites.[2]

Before speaking of the greenstones which occur along the river farther north, it will be well to examine those exposed in the railroad cutting at the western end of the bridge. These rocks are, for the most part, massive, but they nevertheless display evidence of extensive crushing and chemical alteration. No. 11178 represents the average type. This is of a light green color, and in a hand-specimen quite aphanitic. Both macroscopically and microscopically it resembles the massive greenstones so abundant in and representative of the region south of Marquette (see Pl. X, fig. 2). Mineralogically there is hardly a trace of the original rock left. Almost colorless hornblende, pale

[1] Geol. Wisconsin, vol. 3, p. 475.
[2] Rosenbusch: Mikros. Physiog., 2d ed., vol. 2, p. 311.



MAP
of
TWIN AND FOUR FOOT FALLS
Menominee River
(After Brooks)

green chlorite, zoisite, leucoxene and a little calcite (all of secondary origin) are the present constituents; and yet the original structure of the rock is strikingly well preserved. When viewed with a comparatively low power, in ordinary light, the outlines of long, almost acicular, feldspar crystals are very apparent, in spite of the fact that the substance of the feldspar itself is changed to chlorite or zoisite. These outlines of former crystals make a confused aggregate, but each individual preserves its own proper form (idiomorphic in the sense of Rosenbusch). The angular spaces between the feldspars produce a typical example of the ophitic or diabase structure, although no trace of a diabase mineral remains.

But the exposure is not throughout as massive as the specimen just described. It is traversed here and there by schistose and wavy bands which show indications of having been much crushed and rubbed. Slickensides are abundant and lenticular fragments fit into one another so as to produce an imperfect sort of foliation. In other cases, where the crushing has been more intense, the schistosity is more perfect. These bands all strike a few degrees north of west, being apparently conformable to the slates below and the greenstone schists above. This is a suggestive fact when it is remembered, as observed by Brooks, that these slates owe their lamination to slaty cleavage (a product of pressure), which seems to have obliterated the original stratification.

No. 11179, from one of the schistose bands in the greenstone of this cut, shows under the microscope the effects of great mechanical action. Curving and interlacing areas of pale green chlorite and of a grayish substance (perhaps the remains of titanic iron) form the main mass of this rock. Thickly scattered through these are patches of a dark brown substance, often showing concentric zones of a clear, transparent character. These look like opal, but their optical character shows them to be single individuals of crystalline quartz. Imbedded in this material of such pronounced secondary character, are fragments of feldspar, which have been crushed or broken. These, as has been observed so frequently before, are less changed chemically than those in the massive rock from which this schistose band has been derived.

Four specimens were selected to represent the series collected along the river north of the railroad bridge. Two of these came from each side of the river and illustrate both the massive and schistose bands.

No. 11176 was found on the Michigan (eastern) side, just above the bridge. In color it is light green, and in structure it is massive. Under the microscope it shows a pale hornblende in ragged and irregular individuals, feldspar, zoisite, chlorite, and leucoxene. Traces of an original diabase structure are still abundant in this rock. The feldspars often perfectly preserve their lath-like form and their twinning striation, while the pale but compact hornblende occupies the intervening spaces, supplying the place taken by the augite in fresh rocks of this type.

No. 11175, from the highest exposure on the Michigan side of Four-

foot Falls, is quite schistose and of a much darker color than the last rock. Under the microscope it is seen to possess a much finer grain and to be composed of hornblende, chlorite, feldspar, quartz, and leucoxene. The hornblende is for the most part pale green, but that it was bleached from the brown variety is shown by the numerous compact brown cores which occur in the centers of the paler crystals. The structure of this rock is purely granular, with no trace of the diabase type which characterized the specimen last described. This fact and the indication that the pale, fibrous hornblende was derived from a compact, brown variety of the same mineral, render it probable that this rock was originally a diorite, composed of feldspar and brown hornblende, in which little or no pyroxene was ever present. The hornblende of this rock exhibits a structure quite similar to that described by Becke[1] and Van Hise[2] as due to a secondary enlargement of the crystals in a solid rock.

The accompanying figure represents the compact brown interior of a hornblende individual, more or less sharply separated from a pale green or colorless border of hornblende fibers, which possesses exactly the same optical orientation as the core.

FIG. 19.—Compact cores of hornblende surrounded by a fibrous border, No. 11175, a schistose greenstone from Four-foot Falls. Magnified 180 diameters.

Evidence seems to be constantly accumulating that various minerals may continue their growth by regular accretions in solid rocks, whether massive or clastic. This fact is satisfactorily established at least for quartz, feldspar[3] and hornblende. While not in the least doubting the correctness of the conclusions above cited in regard to the secondary growth of hornblende, I must, however, confess that the present isolated instance appears to me hardly to offer conclusive proof that the fibrous hornblende border is a secondary crystalline enlargement. Such an explanation is possible, but the appearance can be equally well explained in my judgment, by assuming that the fibrous zone is the result of bleaching and fraying out of originally compact hornblende crystals. This process would naturally commence at the ends of the crystals and develop principally in the direction of the cleavage, as is here seen to be the case. The only difficulty with this explanation is the sharp line sometimes seen between the brown and the fibrous hornblende. But such a sharp boundary is rather the exception than the rule.

[1]Tschermak's mineral. u. petrog. Mittheil., vol. 5, 1883, pp. 158-59. (cf. Am. Jour. Sci., 3d series, vol. 33, p. 385, 1887.)

[2]Am. Jour. Sci. 3d series, vol. 30, p. 231, Sept. 1885. A. Harker has also recently described similar secondary enlargements of hornblende in a hornblende-picrite from Anglesey. Geol. Mag., London, 3d series, vol. 4, 1887, p. 550.

[3]See Irving and Van Hise: Bull. U. S. Geol. Survey, No. 8.

Nos. 11142 and 11143, taken from two contiguous bands on the Wisconsin side of the river, about midway between the two points which furnished the last described specimens, represent Brooks's localities *l* and *k* respectively. The first is schistose, the second massive. The first is a pale and schistose aggregate of nearly colorless chlorite, light green or colorless hornblende fibers, quartz and calcite. The second is a much darker green mixture of feldspar, hornblende, chlorite and leucoxene. The first named of these components has frequently its crystal form well preserved, which betrays the diabase character of the mother rock. The leucoxene in this section, as well also as in Nos. 11175 and 11176, often possesses the sphene-like habit which has been figured from No. 11189. (Pl. XIII, fig. 1.)

THE TWIN FALLS.

About a mile above the last described rock exposure at the so-called Four-foot Fall, the quiet course of the Menominee River is again interrupted by a very considerable outcrop of greenstone. This is almost continuous for half a mile, but at either end of it the river plunges over a barrier of somewhat harder rock than usual and spreads out below it into a small basin. The two little water-falls thus formed are known as the Twin Falls. In Major Brooks's report they are included in the same map that shows the topography of the Four-foot Fall,[1] and that portion of this map which gives the outlinè of the Twin Falls is reproduced in twice the scale of the original on Pl. VI.

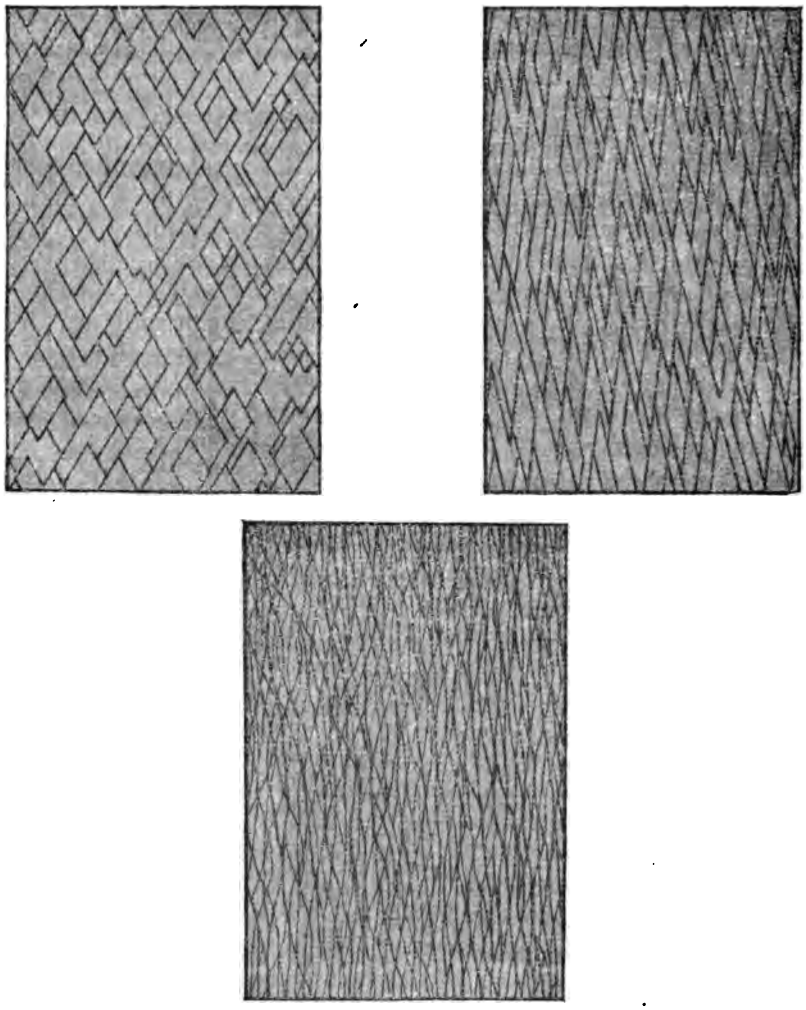
All of these exposures belong to the northernmost of the two greenstone belts of the Menominee Iron Basin. This is much more uniform in its composition than the southern belt, in which the Sturgeon and Quinnesec Falls exposures are located. Its rocks are altogether of a dark green, almost aphanitic type, which, when they become schistose, give rise to dark chloritic slates. Neither the light colored, gabbro-like greenstone, nor coarse diorites, like those of the Horse Race, nor bands of acid rocks occur in the northern belt—at least, not at the localities where this crosses the river.

The homogeneous character of the Twin Falls greenstones is largely due to an advanced state of chemical alteration, which has obscured its original grain.

The macrostructural changes, whereby the compact, dark green rocks are converted from a massive to a schistose state, may be admirably seen along the river banks at both the Upper and the Lower Twin Falls. The foliation of the massive and already chemically altered rock takes place in a somewhat different manner from that heretofore described. There are none of the ragged "cross gashes" and irregular, gaping seams (see Fig. 10, p. 81) which are so common at the exposures along the southern belt. These seem to be the result of stretching in a solid or very nearly solid mass, but in the present case this process is hardly apparent.

[1] Geol. Wisconsin, vol. 3, p. 475, Pl. IV.

The first step toward the formation of a schistose structure in these Twin Falls greenstones (and this is hardly ever absent) is the division of the massive rock by two systems of joints, which stand about perpendicular to the surface and intersect at a varying but acute angle. These joint systems divide the mass into diamond shaped or rhomboidal prisms, the cross sections of which are well displayed upon the frequent smoothly glaciated surfaces of the rock. The appearance of such a surface is diagrammatically represented in Fig. 20.



FIGS. 20-22 diagrams illustrating the transition from jointing to schistose structures in the green stones at Twin Falls.

As we approach the schistose band in the massive rock these interlacing rhombs become lengthened out more and more by an approximation to parallelism between the two systems of joint-planes. (Fig. 21.)

These elongated prisms finally become very much extended lenses, which interlock and produce a well developed, wavy or even parallel schistose structure (Fig. 22). The almost slaty rocks thus produced, especially as seen at Lower Twin Falls, have a tendency to break, not so much along a definite plane as parallel to a line—i. e., the direction, normal to the surface, parallel to which the original joint planes ran. It is difficult to obtain well shaped hand-specimens of these rocks, but narrow rhombic prisms of almost any angle are easily procured. There is an almost equal tendency to cleave along any plane which is parallel to the longest axis of these prisms.

If the prisms due to the original joint planes were subjected to a lateral pressure which developed in them a cleavage that successively approached more and more nearly to the long axis as the prism was lengthened, this peculiar tendency to separate along a line rather than along a plane is precisely the structure which we might suppose would result.

The strike of these schistose bands follows the direction which bisects the acute angle of the rhombic prisms. This is for the most part from S. 70° to 80° E., agreeing with the prevailing strike of all the rocks in this system. There are, however, many exceptions, where these schistose bands, even where near together, follow different directions; for instance, I observed, in the massive though jointed rock on the Michigan side of Upper Twin Falls, two schistose chloritic bands quite near together, one having a strike N. 180° E., and the other S. 73° E., while the dip of each was nearly vertical. Such cases are easily explicable on the supposition that these bands were produced by mechanical agencies, but it is quite impossible to reconcile them with the supposition that these bands are in any way the result of sedimentation.

This type of schistose structure was also noticed to a slight extent at some of the exposures of the lower greenstone belt—notably just below Lower Quinnesec Falls on the Michigan (left) bank of the river (see p. 84). It is, however, there the exception, and is peculiarly the characteristic of the upper belt as exhibited at the Twin Falls.

LOWER TWIN FALLS.

The development of the foliation in the massive greenstone is also shown on a small scale, particularly on the left (Michigan) side of Lower Twin Falls, where there has been a slight amount of slipping along a line of jointing. Fig. 23 gives a diagrammatic idea of a specimen observed at this locality. The area represented is about three feet square. Through the center runs a vein of white quartz which has been depos-

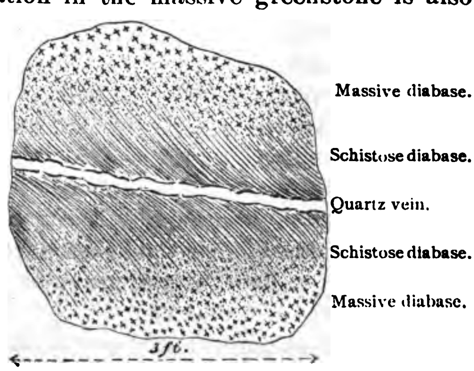


FIG. 23.

ited by infiltration in the old joint seam. On the edges of this the rock is perfectly schistose and chloritic, but it passes gradually, in the space of a few inches, into the massive aphanitic greenstone, which composes almost all of this exposure. Fig. 24 represents a polygonal block, formed by the jointing of the massive greenstone, which has been frayed out into a perfectly foliated chlorite schist by a slipping movement against the adjoining blocks.

The extensive chemical alteration which has gone on in this greenstone seems to render it peculiarly subject to such a fraying out into a chloritic schist. This change takes place in cases where a fresher and harder mass would have received only a slickensides.

FIG. 24.

The Twin Falls greenstones are interesting, in view of the macrostructural alterations which they exhibit. Mineralogically they are all so much decomposed that they present but little which is determinable under the microscope.

The least altered specimen collected is No. 11140, from the east side of the Lower Fall. Together with the specimens shown in Figs. 23 and 24, it came from a steep wall of massive and but little jointed greenstone, which rises abruptly from the water's edge. Diamond jointed and somewhat schistose rocks of the same sort occur on the north (No. 11139) and fissile chloritic slates (striking W. of N. and dipping 70° to the north) to the south of it. Under the microscope this massive rock is found to be a confused aggregate of pale green, somewhat fibrous hornblende, feldspar remnants, and leucoxene, which possesses a sphene-like habit and rarely shows any trace of its original ilmenite. The clearer areas, which represent the former feldspar, are now so filled with actinolite, zoisite, and epidote needles, that nothing regarding the former character of this mineral can be learned. In this rock secondary biotite is also quite abundantly developed, as was found so often to be the case in the Russian metamorphosed diorites described by Inostranzeff[1]. The original structure of this rock is now disguised almost beyond recognition, but it seems to have partaken more of the granular nature of a diorite than of the ophitic nature of a diabase.

No. 11132, taken from the continuation of this mass on the opposite

[1] Studien über metam. Gest., etc., 1879, pp. 81, 82, 109-112.

side of the river, is essentially identical with it, but in it the form of the original feldspars is better preserved. These may often be seen in well formed, lath-shaped crystals, which, in spite of their extensive saussuritization, still retain distinct traces of their plagioclastic twinning striæ. This rock also, in distinction from the one last described, contains some chlorite but no biotite.

These rocks, like so many others of the Menominee River greenstones, are representative examples of the type called by Gümbel "Epidiorit," which is now generally conceded to be an altered form of diabase.[1]

The rocks into which these least altered forms pass are representative chlorite schists and slates; and there can be no doubt that these latter have also resulted from the extreme effects of those metamorphic agencies which changed the eruptive diabase to the epidiorite.

No. 11130, collected just below No. 11132, and grading imperceptibly into it, is a schistose rock, composed of bright green chlorite, finely granular quartz and, perhaps, secondary albite. The leucoxene in this rock is particularly interesting. It still retains small ilmenite cores in places, but it is broken and pulled out in the direction of the schistosity. A very considerable portion of this leucoxene, especially around the edge of the grains, is composed of highly refractive and brightly polarizing, although extremely minute, colorless crystals. These have an octahedral habit and resemble anatase (Fig. 25), which, as both Diller[2] and Rosenbusch[3] have shown, sometimes originates from the alteration of ilmenite (cf. also Nos. 11050 and 11052 p. 121). Biotite also occurs in small quantities in this rock.

FIG. 25.—Anatase derived from ilmenite, No. 11130, from the Lower Twin Fall. Magnified 180 diameters.

At the northwestern corner of the basin, below the Lower Twin Fall (see map Pl. VI), the rock is rhomboidally parted and weathers to a brownish color. In spite of its massive appearance it possesses a latent tendency to cleave along the longest diagonal of the rhomboidal prisms, and this tendency is intensified by weathering. Toward the east this rock (No. 11128) passes gradually into corresponding slates (No. 11129). Under the microscope these two rocks are seen to be in all respects the equivalents of Nos. 11132 and 11130, above described. Their main difference consists in their being richer in iron, which has oxidized and

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[1] Cf. Rosenbusch: Mikros. Physiog., 2d ed., vol. 2, p. 205.

[2] Neues Jahrbuch für Mineral., 1883, vol. 1, p. 191.

[3] Mikros. Physiog., 1st ed., vol. 2, 1877, p. 336; 2d ed., vol. 1, 1885, p. 332, cf. also Schenck; Inaugural Dissertation, Bonn., 1884, p. 25.

stained the rocks brown. No. 11128 still retains much hornblende, feldspar, and ilmenite, and the diabase structure is still apparent in places. No. 11129 is, like its counterpart No. 11130, a chlorite schist with the hornblende replaced by chlorite, the feldspar by a quartz albite mosaic, its leucoxene drawn out, and its structure wholly changed.

Perhaps the most altered rock of any encountered at the Lower Twin Fall is No. 11139, which was one of the chloritic slates on the Michigan side of the river below the massive rocks. This is a very fine grained aggregate of pale green chlorite, quartz, or quartz albite mosaic and biotite, the latter constituent being sparingly present. Sharply defined crystals of tourmaline are also abundant in this rock.

UPPER TWIN FALLS.

At the Upper Twin Fall the same massive greenstones with a rhomboidal parting prevail, everywhere traversed by more or less schistose bands. No. 11133 is the massive rock from the left or Michigan side of the fall. It is much altered chemically, but preserves its original structure almost perfectly. When examined by a low magnifying power there is seen a network of light colored, lath shaped feldspar forms, which are almost acicular, like those of a porphyrite. Between these is an allotriomorphic mass of a dark gray substance, representing the former augite, or possibly a glassy base. When examined more carefully with a higher power, the feldspar is found to be completely replaced by a mixture of pale green chlorite and brown biotite in the closest relationship, while in them an occasional crystal of zoisite is imbedded. The darker interstitial mass is composed largely of fibrous hornblende in shreds or confused, matted masses, but these are mingled with much impure and indeterminable matter.

Two schistose bands have already been mentioned on p. 129 as traversing this rock in different directions. Of these, the one striking S. 73° E. is the less schistose, and is represented by specimen No. 11135. Though much more altered than the last, there are here also occasional unmistakable traces of the same ophitic structure. The representative of the other band, No. 11134, is hardly more than a fine schistose aggregate of chlorite, quartz, and calcite, with only the faintest indications of its original structure, and yet here there are beautiful leucoxene borders around unaltered cores of ilmenite. Narrow veins filled with a mixture of calcite and chlorite traverse all these rocks.

On the opposite or Wisconsin side of the Upper Twin Falls the rocks are apparently the same, but they show, nevertheless, important microscopic differences. The massive forms represented by Nos. 11122, 11125, and 11126, collected at different points between the falls and the bridge, are fine and confused aggregates of pale green, fibrous hornblende, chlorite, zoisite, quartz, leucoxene, and occasionally (No. 11122) a little biotite. All of these minerals are of secondary origin and in

the process of their formation most of the traces of the former rock-structure have been obliterated. Such traces as still remain indicate that the mother-rock was a diabase, but there are seen none of the long, acicular feldspar forms, discovered in the rocks from the opposite side of the river.

The schistose bands interlaminated with these rocks are quite like those already described. One of these, however, No. 11123, obtained directly beside the falls, shows almost the only evidence of fragmental origin anywhere observed in the Menominee greenstones. This contains irregular and angular fragments of quartz and a slightly altered feldspar of considerable size. These are imbedded in a matrix of irregular grain, composed of chlorite, calcite, quartz, and opaque iron oxide, which is accompanied by leucoxene. The chlorite scales often have a radially divergent arrangement around the larger included fragments of quartz and feldspar.

Thin section, No. 11122, shows the contact of this schist with the massive rock. This contact is so sharp as to lend much additional probability to the idea that in this case the two rocks are of different origin.

Rocks of this kind are to be regarded as diabase-tuffs, similar to those which are so largely developed around Marquette, and which are to be described in the sequel. It is easy to see how essentially the same material, whether produced as volcanic ash or as a massive rock, when subjected for a long period to the action of the same metamorphosing forces, would give rise to masses which, in certain cases, could not be distinguished from one another. This is undoubtedly true of many occurrences on the Menominee River, and hence we can speak with certainty only of those instances where sufficient of the original structure is preserved to do away with all doubt. Between undoubted massive rocks rendered schistose by pressure on the one hand, and fragmental tuffs which have been more or less completely solidified by the same agency on the other, there must therefore be rocks whose original form must always be uncertain.

CHAPTER IV.

GREENSTONE BELTS OF THE MARQUETTE DISTRICT.

INTRODUCTORY.

Ever since the discovery of iron in the northern peninsula of Michigan, in 1844, by Burt and Houghton, the region around Marquette has received much attention from geologists. Although not so early known as the famous copper district of Keweenaw Point, this iron region has divided the scientific interest which was before felt in the copper-bearing rocks.

Douglass Houghton,[1] Locke,[2] Foster and Whitney,[3] Whittlesey,[4] Kimball,[5] Credner,[6] Brooks,[7] Wright,[8] Wadsworth,[9] Rominger,[10] and Irving[11] have studied the general relations of the deposits, while microscopical descriptions of some of the rocks have been given by Julien,[12] Wright,[13] Wichmann,[14] Pumpelly,[15] Wadsworth,[16] and Irving.[17]

The city of Marquette is situated on the south shore of Lake Superior, about midway between the Carp River and the promontory known as Presqu' Isle, between which points (a distance of about 4 miles) the lake shore runs nearly north and south. The city for the most part lies within the square mile designated as Sec. 23, T. 48 N., R. 25 W., Michigan.

An excellent idea of the topography of this region and of that extending for 18 miles back of it (i. e., westward from the lake) may be obtained from the large colored map prepared by Dr. C. Rominger.[18]

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[1] Brooks, Geol. Michigan, vol. 1, 1873, p. 13.

[2] Geol. Michigan, vol. 2, 1873, p. 239.

[3] Senate Docs., 1st session, 30th Congress, 1847-'48, II, Doc. 2. Report on the Geology and Topography of the Lake Superior Land Dist., Part II, Iron Region.

[4] Proc. Am. Assoc. Adv. Sci., 1859, vol. xiii, part 2, pp. 301-308; ibid., 1875, vol. 24, part 2, pp. 60-72.

[5] Am. Jour. Sci., 2d series, vol. xxxix, 1865, pp. 290-303.

[6] Zeitschr. Deutsch. geol. Gesell, vol. xxi, 1869, pp. 516-554.

[7] Geol. Michigan, vol. 1, 1873, part 1. pp. 1-319.

[8] "Geology of the Lake Superior Iron District" in Swineford's History and Review of the Copper, Iron, Silver, Slate, and other Material Interests of the South Shore of Lake Superior, 1876, pp. 132-145.

[9] Bull. Mus. Comp. Zool., Cambridge, vol. 7, No. 1.

[10] Geol. Michigan, vol. 4, part x, Marquette Iron Region, 1881, pp. 1-154.

[11] Preliminary paper on an Investigation of the Archean Rocks of the Northwest; Fifth Ann. Rep. U. S. Geol. Survey, 1886, pp. 181-242.

[12] Geol. Michigan, vol. 2, 1873, Appendix A.

[13] Geol. Michigan, vol. 2, 1873, Appendix C.

[14] "Microscopical Observations of the Iron-bearing (Huronian) Rocks from the region south of Lake Superior," 1876, Geol. Wisconsin, vol. 3, pp. 600-656.

[15] Am. Jour. Sci., 3d series, vol. x, 1875, pp. 17-21.

[16] Bull. Mus. Comp. Zool., vol. 7, No. 1.

[17] Bull. U. S. Geol. Survey No. 8, pp. 27-30.

[18] Geol. Michigan, vol. 4, 1881, in pocket.

The general trend of both the drainage and of the geological formations within this area is toward the east. The two main streams follow somewhat irregular but approximately parallel (eastward) courses and empty into the lake about four miles apart. The more northerly of these is called the Dead River; the more southerly the Carp.

The general surface of this area rises by degrees from the level of the lake to an elevation of about 1,000 feet above the lake. This surface is, however, extremely broken and hilly, being traversed by east and west ridges composed of rows of rocky knobs. These elevations are never over two hundred feet in height from the base; usually they are much lower (from one hundred to fifty feet or even less). They all have rounded outlines produced by the wearing action of the great glacier, evidences of which are everywhere apparent in the smoothly polished and frequently striated rock surfaces. These knolls rise from the even level of a plain produced by the glacial débris deposited between them.

An account of the general geological structure of the Marquette region has already been given in Prof. Irving's explanatory note at the beginning of this paper, in which is included also a summary of the different views held by various writers with regard to the stratigraphical position and origin of the rocks of the greenstone-schist area, which forms the subject of this part of the present essay. In connection with this account has also been given a geological map of the Marquette region, compiled by Professor Irving from the maps of Brooks and Rominger and from original observations of his own. (Pl. I.) It will not therefore be necessary for me to present anything further as to these general matters in the present connection.

Special references to the petrographical work of others on the Marquette rocks will be made in the course of the following detailed descriptions.

In some respects the greenstones of the Marquette area seem peculiarly suited to throw light upon the dynamic metamorphism of basic eruptives, since a portion of these rocks seem to have been extruded both during and subsequent to the action of the metamorphosing forces. Hence we find the same eruptives in different stages of alteration. Moreover, fragmental material (tuff) of the same nature and origin of the massive rocks is abundantly developed, and this too shows varying stages of consolidation into masses which closely resemble the solid rock. This great variety, while it is full of interest and suggestions of new possibilities, is frequently very confusing. It often becomes impossible to speak with certainty about the origin of a rock which, on account of its many analogies, we may regard as having been produced in several different ways.

The general similarity of the greenstone schists of the Marquette and Menominee areas will be brought out in the following pages. It is worthy of mention that the greenstone schists of both of these regions have a strong resemblance to some of the greenstones and agglom-

erates of the extensive group of rocks occurring on the Lake of the Woods and on Rainy Lake in Canada, to which Mr. Andrew C. Lawson, of the Canadian Geological Survey, has given the name of Keewatin series. This series he regards as belonging immediately beneath the Huronian, which is represented in those northern regions by the so-called Animiké series.[1] This is also the position which the greenstone schists of Marquette occupy, since they quite unmistakably underlie the iron-bearing detrital rocks, which, according to Irving, are the equivalents of the true Huronian. According to Irving also the greenstone schists here probably underlie the overlying iron-bearing series unconformably.

The Marquette greenstone-schist belt, which at the lake shore is between 2 and 3 miles wide, extends to the westward for about 6 miles, without materially altering its form or width. It then broadens suddenly by a wide extension toward the north, and at the same time is divided into two portions by the eastern extension of a narrow arm of granite (See map, Pl. I). The southern of these portions continues a due westward course with an average width equal to that of the entire belt before its division. The northern portion is separated from the southern, first by granite, and then to a greater and greater extent by a large, wedge shaped area of the rocks of the overlying iron-bearing or Huronian series.

For convenience in arranging the following petrographical descriptions the ground covered has been divided into four areas, which will be considered in order: (1) The *eastern* area, near Marquette; (2) the *western* area, immediately north of Teal Lake, in the town of Negaunee; (3) the *northern* area, lying north of Dead River, and (4) the *Deer Lake* area, a short distance north of the town of Ishpeming. The last named area was not studied by the writer in person, specimens from it, with full descriptive notes, having been sent to him by Professor Irving for comparison with the collections which the writer had himself made in other areas.

In the eastern or Marquette area the whole width of the greenstone belt, including the granite contact on the north, was studied for a distance of 3 miles west from the lake shore. In the western or Negaunee area two sections were run northward across the greenstone-schist belt, one passing through Secs. 21, 28, and 33, T. 48 N., R. 26 W.; the other through Secs. 13, 24, 25, and 36, T. 48 N., R. 27 W. In the northern area the examinations made were carried on from a camp situated in Sec. 9, T. 48 N., R. 26 W., and embraced the area covered by Secs. 3, 4, 5, 8, 9, 10, and 11 of this township.

The first of these areas is the most varied in its petrographical characters, and it was, therefore, the most thoroughly studied. It is

[1] See General Report of Progress of the Geological Survey of Canada for 1885; also of Am. Jour Sci. (3d series), vol. 33, 1887, p. 473. I am indebted to Dr. Lawson for the opportunity of examining the extensive suite of the Rainy Lake rocks, upon the microscopical study of which he was engaged in the petrographical laboratory of Johns Hopkins University in the winter of 1886-'87.

divided into two portions of nearly equal extent by the narrow east and west band of iron-bearing slates, to which Rominger applied the name of Eureka series. The northern portion of the Marquette area, extending from Lake street, Marquette, northward to the granite, is in large part composed of banded greenstone schists, having an east and west strike, and a steep northern dip. They are most conveniently seen in typical development on Lighthouse Point. The layers of these rocks are alternately of a darker and lighter shade of green, which gives these particular greenstones their characteristic striped appearance. In these banded rocks of the northern part of the Marquette area intrusions of comparatively little altered acid and basic matter are abundant. These are for the most part conformable to the bedding of the schists and embrace granites, gneisses, schistose porphyries, diorites, and diabases. Whenever, in these undoubtedly eruptive rocks, a schistose structure is apparent, this is conformable to the bedding of the banded greenstone schists.

The southern portion of the area about Marquette, on the other hand, is occupied by much more massive and homogeneous greenstones of a nearly uniform light green color, and an almost aphanitic structure. These are characterized by their division into oval or lenticular areas which interlace and which are separated by a finely schistose material of much finer grain. This peculiar parting, which, according to the writings of the Canadian geologists, appears to have a very widespread distribution through the greenstones of the Northwest, at first glance resembles the spheroidal weathering of many eruptive rocks. There is, however, better reason for regarding it as of mechanical origin, as will be more fully explained in Chap. V.

The schistose structure of the southern Marquette greenstones is of secondary origin, due, probably, in almost every case, to pressure, while anything like the banding or striping of the more northern rocks is here wholly wanting. Intrusive rocks are rarer than in the banded greenstones of the northern portion of this area. When such dikes do occur they are much more altered and hence approach closely to the enclosing rock—a fact which renders their detection difficult.

The two portions of the Marquette greenstone area are therefore broadly distinguished in many of their petrographical characters. The east and west band of iron shales, mentioned above as separating them, extends from the north side of Marquette harbor (Lake street) westward along the northern side of the Duluth, South Shore and Atlantic Railroad. They seem to be identical with certain members of the iron series and at one point, about two miles west of Marquette, they actually contain quite an extensive deposit of hematite. It is here that the Eureka shaft was sunk at an early date in the history of iron mining in the Marquette region, and from this Dr. Rominger has taken his name for this series of Huronian beds. To make the references to localities in the Marquette area more intelligible, a sketch map of the environs of the city is here appended, Pl. VII.

With reference to the other two areas examined it is here sufficient to say that the greenstones of the western or Negaunee area more closely resemble those exposed in the southern portion of the Marquette region; while the rocks encountered in the northern area show many points of likeness to those occurring north of Marquette.

ROCKS OF THE NORTHERN PORTION OF THE MARQUETTE AREA.

BASIC INTRUSIVES.

Diabase.—Diabase in well defined dikes of various sizes is an important feature in the geology of the northern portion of the Marquette greenstone area. This rock occurs in all stages of preservation from an unaltered condition to a hardly recognizable aggregate of secondary and decomposition products.

In all the freshest specimens examined olivine is present, but with the commencement of alteration this mineral is the first to disappear In many cases, therefore, where the rock may still be recognized as a typical diabase, it is now impossible to say whether it was originally olivine-bearing or not.

The next stage in the alteration is marked by the change of the pyroxene to uralite, and the more or less synchronous passage of the feldspar into saussurite and of ilmenite into leucoxene.

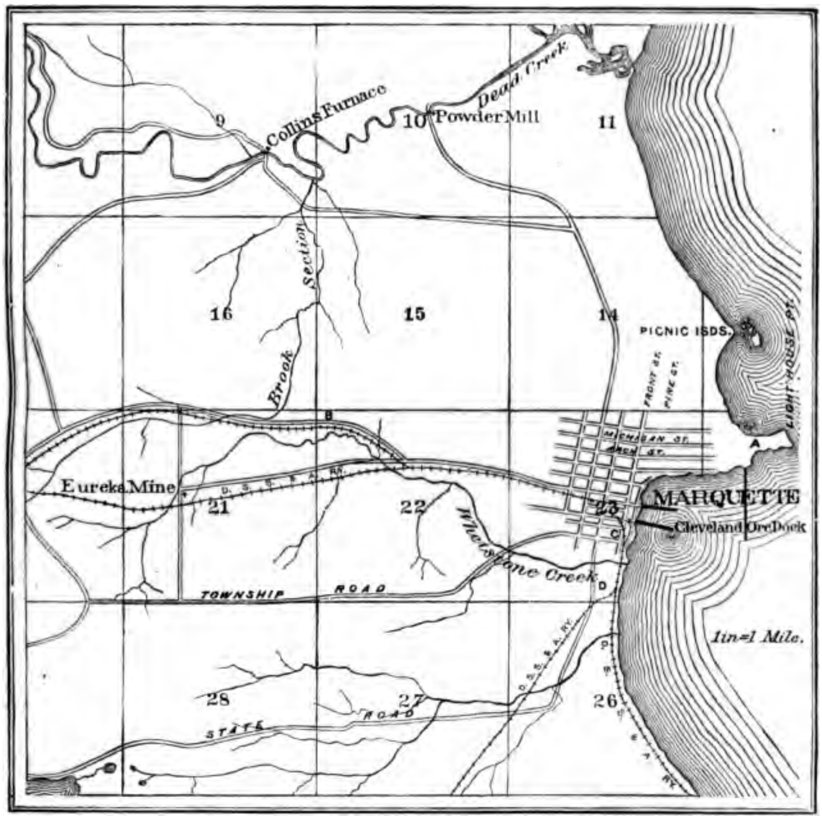
Still later follows the development of such final decomposition products as chlorite, epidote, calcite, quartz, etc. The extent to which these chemical changes destroy the original diabase structure differs in different cases. As a rule this remains distinct during the first two stages of alteration, while it generally, though not always, disappears during the third. In some instances a pronounced schistose structure has been developed in undoubted diabase dikes by extensive alteration.

The Great Dike.—The best material for the study of the fresh olivine diabase near Marquette was obtained from the great dike which forms the center of Lighthouse Point (see Pls. I and VII). Here its eruptive character may be admirably seen by the sharp line of contact which it presents with the adjoining banded green schists. This dike may be traced by several outcrops along Michigan street in Marquette, and then as a high, rocky ridge which extends for some three miles westward, through Sections 15 and 16, just north of the main road from Marquette to Negaunee.

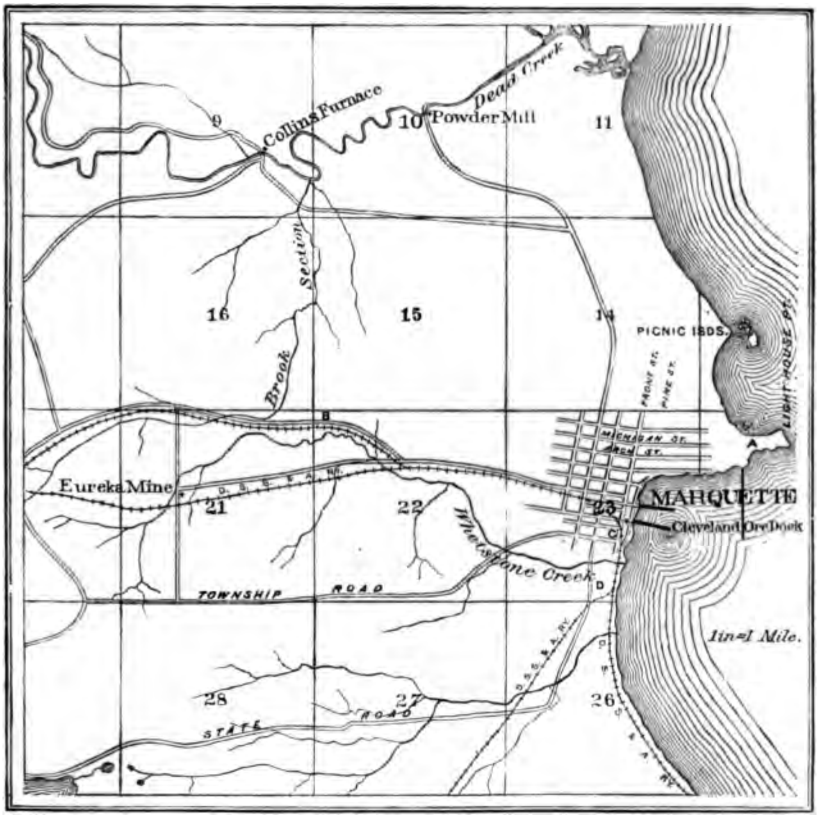
From various portions of this dike nine specimens were collected. The four freshest of these specimens (Nos. 11617 and 11622, from Lighthouse Point; No. 11636, from Lighthouse Point quarry, and No. 11666, from a cutting on Michigan street) are not to be distinguished from one another.

The structure of this work is the hyp-idiomorphic diabase structure,[1] which forms one of the most certain characteristics of this group

[1] "Structure ophitique" of Fouqué and Michel-Lévy, "Divergent-strahligkörnige Structur" of Lossen, and "Diabasischkörnige Structur" of Rosenbusch.



MAP OF THE ENVIRONS OF MARQUETTE



MAP OF THE ENVIRONS OF MARQUETTE

of eruptives. The grain is of medium coarseness. The lath-shaped plagioclase crystals measure from 1.5 to 1^{mm} by 0.25 to 0.15^{mm}. The interstices between these are filled with augite and ilmenite. The mineral components observed under the microscope are, in order of their age, as follows:

Essential: Olivine, labradorite, augite, $\left\{\begin{matrix}\text{Ilmenite,}\\ \text{Magnetite.}\end{matrix}\right\}$

Accessory: Apatite, hornblende, biotite, quartz.

Secondary: Serpentine, uralite.

The olivine is mostly in rounded grains or in irregular areas, although it sometimes shows evidences of a crystal form, especially the acute angle due to the intersection of two dome faces (notably in No. 11666). It is commonly wholly changed to serpentine, but in a few instances remnants of the original transparent olivine substance remain.

The feldspar is always a plagioclase with the peculiar elongation of the crystal in the direction of the brachydiagonal axis, which is characteristic of diabase. The crystals are always striated, often minutely so. The extinction is generally sharp, although an undulatory extinction is sometimes observed.

The augite is quite normal for diabase. It is of a light, slightly reddish shade of gray, with a perfect cleavage parallel to the prism. Twins are very common, and the line of the lamellæ may be seen in ordinary light traversing the basal sections and bisecting the cleavage angles. In polarized light the colors distinguishing the twin lamellæ are very brilliant. No crystal form is ever recognizable, the mineral being typically "xenomorphic," in the sense used by Rohrbach.[1]

Quartz is rare in diabase, but where it occurs as it does in No. 11666 we must regard it as an original constituent, on account of the extreme freshness of the whole specimen.[2]

The iron oxide is entirely opaque and shows a very irregular outline. This is mostly due to the penetration into it of the feldspar crystals whose form is clearly shown. Its crystallization must therefore have been subsequent to that of the feldspar, and was apparently about synchronous with that of the augite. The oxide itself is probably partly ilmenite and partly a titaniferous magnetite. In none of the freshest specimens does it show trace of leucoxene. It is, however, sometimes partially surrounded by a border of biotite.

Original hornblende is rare in this rock, but traces of it were observed in a few instances.

Among the alteration products serpentine is abundant wherever olivine existed, but the rock is still too fresh to show more than the most occasional uralitization of the pyroxene.

The five other specimens collected from this great dike show more

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[1] Tschermak's mineral. u. petrog. Mittheil., vol. 7, 1885. Rohrbach's two terms, "authomorphic" and "xenomorphic," adopted by Kalkowsky (Lithologie, 1886, p. 14) were replaced by Rosenbusch in the last edition of his Massige Gesteine by "idiomorphic" and "allotriomorphic," though for what reason is not apparent.

[2] Cf. Rosenbusch, Mikros. Physiog., 2d ed., vol. 2, 1886, p. 188.

altered forms or abnormal varieties of the same rock. They are as follows:

No. 11621, glassy diabase.
No. 11675, granophyre diabase.
No. 11672, uralite diabase (structure intact).
No. 11615, uralite diabase (structure intact).
No. 11610, epidiorite schist (structure gone).

No. 11621, collected near No. 11622 from the side of the great dike on Lighthouse Point, is a glassy modification of the diabase, produced by the rapid cooling of the molten mass against the inclosing walls. The microscope shows this rock to be composed of a very dark brown glass, which can be rendered transparent only with the greatest difficulty. This opacity is due to the accumulation of minute globulitic bodies, which can be detected only with the highest magnifying power in the thinnest parts of the slide. Traces of the arborescent and fern-like forms common in basic glasses (tachylite) are easily recognizable. The only mineral constituents which have crystallized in this rock are olivine and feldspar. The former shows well defined crystals. These frequently contain inclusions of the brown glass, and are now wholly changed to a yellowish green serpentine. The feldspar shows the narrow, lath-shaped, and but partially completed crystalloids and skeleton forms which abound in all glassy rocks. These are filled with either penetrations or inclusions of the brown, glassy base.

The chemical constituents of the other diabase minerals—augite, ilmenite, etc., are still present in the glass.

No. 11675 presents an unusual modification of this diabase. The specimen was collected from the high, rocky ridge which is formed by the great dike in the southern part of Section 16, about one and a half miles west of Marquette. The hand-specimen is browner than is usual in this diabase and is speckled with reddish spots. Under the microscope the grain is found to be of the usual coarseness and the rock itself slightly more altered than the specimens above described.

The structure of the rock is still perfectly preserved. The ilmenite is unaltered, and, as before, is frequently fringed with biotite. The feldspar is clear and its twinning striations are very distinct, although it is traversed by many interlacing veins of a green chloritic alteration product. There are no certain traces of olivine in this rock and the augite has undergone extensive change to a brownish yellow hornblende. This is partly fibrous, but also in part quite compact. Indeed, this rock offers a noteworthy instance of the apparent change of augite directly into compact brown hornblende. Much more of this mineral is here present than in any of the fresher specimens examined. It is impossible to assert positively that some of it did not exist as an original component of the rock, but the frequent cases of its undoubted derivation by paramorphism of the augite makes it at least probable that all the hornblende has originated in this way.

The reddish spots spoken of as visible in the hand-specimen represent another interesting feature of this rock. They are shown by the micro-

scope to be areas of a regular intergrowth of feldspar substance and quartz. This is sometimes in the form of granophyre. i. e., in slender fibers, which group themselves in radiating tufts about a clear feldspar crystal, and sometimes it shows the structure called micropegmatite. This latter consists of small angular areas of quartz, each having the same optical orientation, which are embedded in the reddish globulitic feldspar substance.[1]

Quite recently Mr. Waldemar Lindgren has described a similar structure in a diabase from the Big Belt Mountains, Montana.[2]

It was also observed by the writer some years ago in a diabase from Pleasant Valley, New Jersey, a specimen of which he received from Mr. J. F. Kemp, of Cornell University.

Rosenbusch[3] regards this structure as sufficient proof that the quartz is original, but the observations of Irving[4] in the Keweenawan felsites and others make this conclusion doubtful.

No. 11672, collected at the corner where the road running west from Collins Furnace joins the road leading to Bancroft on the Dead River (center of Sec. 17, T. 48 N., R. 25 W.), is a uralite diabase, whose structure is still perfectly preserved.

The large crystals of idiomorphic feldspar are in part clear, but to a considerable extent clouded by the development of saussurite.

The allotriomorphic augite is in some cases intact or remains as a core in the center of the secondary hornblende which has been derived from it. More frequently, however, the hornblende or uralite has wholly replaced the pyroxene. Its structure is oftener compact than fibrous, and its form reproduces exactly that of the original augite. Quartz areas are not uncommon. The ilmenite is mostly changed to leucoxene. Near one large grain of the latter is seen an area of brown mica, which is filled with a sagenitic network of minute rutile needles.

No. 11615, from an outcrop of this same great dike, at the bottom of the hill, which forms the eastern end of Arch street, Marquette, represents the next stage of alteration in the diabase.

The original structure is still plainly recognizable, although it is beginning to be concealed by alteration.

The feldspars exhibit their characteristic lath-like forms, but the sharpness of the outlines and more or less of the internal substance is clouded by secondary products. These seem to be for the most part small hornblende needles which have wandered in from the alteration of the pyroxene, but in some places epidote is also developed from the alteration of the feldspar itself. Still, in nearly every case enough of this unchanged feldspar is present to show plainly its original form and twinning structure.

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[1] This peculiar structure was first observed in diabase by Törnebohm in 1877 (Neues Jahrbuch für Mineral., 1887, p. 262), who found it in his Konga-diabase type of southern Sweden, and named it "Schriftfeldspath."

[2] Tenth Census Repts., U. S., vol. 15, 1887, p. 736.

[3] Mikros. Physiog. 2d ed., vol. 2.

[4] Cf. Mon., U. S. Geol. Survey vol. 5, p. 114.

The augite is in the process of changing to hornblende. This alteration is sometimes complete, but oftener cores remain in the center of what was the original pyroxene crystal. The border of hornblende is double, consisting of a wider internal band of yellowish brown fibers which have apparently resulted directly from the augite substance, and a narrower, outer zone of bright emerald green, pleochroic needles which seem to project into the surrounding feldspar.[1] The individuals of the inner zones are much smaller than those of the outer, and form a confused, felt-like mass, while the external needles as a rule have their longest axes parallel. These needles are most developed in the direction of the vertical axis of the augite. They may owe their different coloring to the influence of the feldspar substance which has contributed to their formation. In some cases the secondary hornblende appears to be homogeneous over considerable areas, exhibiting a uniform extinction and a comparatively compact character. This can not, however, be regarded as original in its nature.

The ilmenite still retains its form but is largely changed to leucoxene.

No traces of olivine were found in this rock, probably because of its altered condition.

No. 11616 is instructive when taken in connection with the specimen last described, No. 11615. Both were collected from the large and smoothly glaciated surface of trap, exposed at the east foot of Arch street. Through the massive rock run a number of schistose bands, produced by crushing and shearing along lines of weakness. One of these bands furnished the present specimen. There can be no doubt that these bands are a part of the massive rock. Both were the same before the schistose bands were produced by more intense mechanical and chemical action.

Under the miscroscope the appearance of these two specimens is found to accord fully with their field relations. The original diabase structure, so distinct in the massive rock, has wholly disappeared in the schistose one. There are no traces of lath-shaped feldspar left. The rock is mainly composed of a confused network of fibrous, very pale green and slightly pleochroic hornblende needles. These are sufficiently parallel in their arrangement to produce the schistose structure of this rock. They are secondary—formed from the alteration of the augite or the joint alteration of the pyroxene and feldspar—as may be admirably seen in section No. 11615, where they are in the process of formation. Scattered among this hornblende, is considerable cloudy and nearly opaque saussuritic substance, mixed with more or less secondary quartz, both of which have been derived from the feldspar. The ilmenite also has undergone an interesting alteration and is here represented by cloudy leucoxene, with only occasional opaque black dots of the original mineral. This substance is arranged in long stringers and shreds which follow the direction of the schistose structure.

[1] On the production of a similar double uralite zone around pyroxene. See Lossen: Erläut. z. geol. Specialkarte von Preussen u. d. thüring. Staaten, Blatt Harzgerode, p. 81, 1882; and Williams: Bull. U. S. Geol. Survey, No. 28, p. 42, Pl. I, Fig. 2.

Here we have an undoubted instance of the dynamic metamorphism of a diabase, where every stage in the process can be followed. Every mineral of the schist can with certainty be traced to its original form, and yet the chemical alteration has been accompanied by such a change of position (migration) that the original structure has wholly disappeared and a new and different structure has been produced. This derived rock is quite identical with some of the most characteristic so-called hornblende or actinolite schists.

The chemical action has here been proportionately increased by the crushing. This seems true for all the constituents, as there are no traces of the fresh fragments of broken feldspar crystals which were so often observed in analogous greenstones of the Menominee region.

There is an excellent section through the rocks of the northern portion of the Marquette area, exposed by a brook which flows northward almost along the line between Sections 15 and 16 (hardly over a mile west of the city) and empties into Dead River. Between the road leading from Marquette to Collins's Furnace and that forming the main highway to Negaunee, this small stream has excavated a deep ravine, upon the high, steep sides of which the relationship of the different rocks is admirably diplayed. This locality is described by Dr. Rominger,[1] and for convenience we will in future allude to it as the Brook section. (See Pl. VII.)

Here were encountered several exposures of fresh olivine diabase. One of these, No. 11708, was taken from the branching dike in the wall of greenschist and granite, which Rominger has described and figured.[2] This rock resembles the freshest specimens obtained from the great dike, except that its grain is finer, as might be expected in a mass of so much smaller size. No trace of alteration is here visible, except in the olivine. This constituent is not abundant, but it occasionally appears in well shaped crystals, which are completely changed to yellow serpentine. The iron oxide presents in its form a decided contrast to that above described. In this rock it was produced much earlier than in the other, and hence it has a well developed crystal form. This, as seen under the microscope, is square (octahedral section), which may be an indication that the mineral is magnetite instead of ilmenite, as before. The feldspar and pyroxene of this rock need no special comment.

No. 11719, obtained near the edge of another dike not far from the last mentioned one, is only semi-crystalline. Its brown, glassy base resembles that of No. 11621, but crystallization is farther advanced. The sharply defined olivine and feldspar crystals are quite the same, but a vast number of smaller feldspar crystals are here developed in the base. Only a very little augite, and that in rounded grains, is present. This rock would be correctly termed a melaphyre.

[1]Geol. Michigan, vol. 4, p. 25.
[2]Ibid., p. 148.

No 11679 is from the center and No. 11680 from the edge of a dike of porphyritic greenstone, which intersects the banded greenschists on the western side of the Brook section, not far from its southern end.

The first of these rocks has a coarsely porphyritic structure, which, on account of its altered condition, is only prominent on a weathered surface. A fresh fracture appears of an almost even gray color, resembling some of the finer greenstones. Under the microscope this specimen is found to correspond admirably to the descriptions of the rock-type, named by Gümbel "epidiorite." The augite, reddish brown cores of which still remain, is largely changed to fibrous hornblende. This mineral is mostly of a pale brown color, but often has a bright green edging where it adjoins the feldspar substance, as has already been noted in the case of No. 11615 (p. 141). The feldspar is still clear and fresh, showing the characteristic lath-shaped forms of diabase. It is only rarely clouded by small patches of a gray saussurite. Much more abundant in this feldspar are veins and small areas of green hornblende needles, which owe their existence mostly to the pyroxene, though the feldspar seems also to have aided in their formation. They are especially abundant in cracks, along which the substance appears to have wandered from the decomposing augite. This hornblende is finely fibrous and forms matted, felt-like masses. There is but little chlorite and secondary quartz in this rock. The ilmenite is largely changed to leucoxene and occasionally surrounded by a rim of biotite.

The second of these two specimens (No. 11680) from the edge of this dike, shows an extremely fine grained, greenish groundmass, whose components are very weakly polarizing and hardly determinable. This was perhaps once a glass which has become devitrified and viriditic. In it are imbedded sharp, lath-shaped plagioclase crystals, which are either unaltered or at most penetrated by veins of actinolite needles, and augite almost wholly changed to hornblende or chlorite.

The following five rocks are also good representatives of the epidioritic type. They are largely composed of either light or dark green, fibrous, secondary hornblende. In none of them does any trace of augite now remain, and it is possible that some of them were originally true diorites, like the rocks to be described under the next head. However, the unmistakable evidences of diabase structure often apparent render it more probable that these rocks all belonged originally to this type.

No. 11663, from Pine street just north of Michigan street, Marquette, is most like a true diorite and may be an altered form of the Picnic Island rock. The hornblende is of the general type represented in Pl. XII, fig. 2 of No. 11186, from the Horse Race above Upper Quinnesec Falls (see p. 107). It is more or less fibrous, of a pale green color and often looks as though it had originated from the bleaching and disintegration of a compact original hornblende. Around the edge of large areas it has a darker green border and seems to ravel out into fine fibers which

wander into the feldspar. Indeed, the feldspar is quite filled with such hornblende needles, which, together with its saussuritic alteration products, almost conceal the original substance. Ilmenite in ragged areas, but without leucoxene, and a little of the chlorite-epidote aggregate (see Pl. XI, fig. 1) are also present.

Nos. 11712 and 11720, both from the Brook section, are rocks of the same general character as that last described. The former is decidedly schistose and bears much internal evidence of the action of great pressure. All of the constituents are arranged in interlacing and elongated bands. The feldspar is much crushed and shows the peculiar mosaic due to secondary crystallization. It is also often changed to a granular aggregate of brightly polarizing, pale green epidote grains. The hornblende crystals are broken and bent, and especially around their outer edge, are very frequently reduced to a confused mass of fine needles which have extensively wandered out into the feldspar substance. The ilmenite also is much crushed and elongated in the direction of the schistosity, but it shows no indication of being changed to leucoxene.

The second specimen, No. 11720, is somewhat schistose, though less so than the last. It is extremely dark in color owing to the large proportion of iron which enters into its composition. Under the microscope it is a confused aggregate of very dark green and strongly pleochroic hornblende needles, a little feldspar, proportionately much ilmenite and quartz. Some of the larger hornblende crystals show the peculiar granulated center, lately described and figured by me from the gabbro-diorites occurring near Baltimore,[1] to which indeed this specimen presents many points of close resemblance.

The two remaining specimens are much more altered than those just described.

No. 11661, found beside the granite boss (the so-called "gold mine") just west of Pine street, Marquette, is coarsely granular. The feldspar is altered to saussurite or calcite. The hornblende is pale green and partly fibrous. The center of the crystals is frequently composed of a dark, yellowish green substance which hardly polarizes at all. This, at first glance, appears to be a core of compact brown hornblende but a closer examination shows that this is not its nature. A little sphene and considerable blood red iron hydroxide make up the remainder of this rock.

The last specimen of these epidioritic rocks, No. 11711, was part of a well marked dike of schistose greenstone which intersects a boss of gneiss near the northern end of the Brook section. This gneiss strikes E. and W., while the dike strikes N. 75° E. The schistosity of the latter is parallel to its walls, so that the foliations of the two rocks intersect at an angle. This rock shows the effects of pressure and crushing. It is now a finely granular aggregate of pale green fibrous hornblende, feldspar, quartz, calcite, and leucoxene.

[1] Bull. U. S. Geol. Survey, No. 28, p. 28, Pl. III, fig. 1.

Diorite.—The occurrence of typical original diorite in the Marquette area still seems a little doubtful. No. 11654, which composes the Picnic Islands, a short distance north of Lighthouse Point, comes nearest to deserving this name, although this rock might with as much propriety be termed an amphibole granite. Julien called it a "quartzose porphyritic diorite,"[1] and he was followed by Wadsworth.[2] The microscope shows this rock to be a coarsely granular aggregate of green hornblende, saussuritized plagioclase, together with a less altered, unstriated feldspar, quartz, and sphene. The hornblende is mostly quite compact, and shows in cross-section sharp crystalline outlines, which are often twinned. The plagioclase contains large zoisite individuals aside from its more usual saussurite aggregate. The unstriated feldspar seems to alter to muscovite or kaolin, as is common in orthoclase. Seams in this rock are filled with epidote, calcite, or more rarely specular iron.

The Picnic Island rock seems to be most closely related to the amphibole-granites, gneisses, diorites, and massive hornblendite which occur in the granite farther north—notably on Partridge or Middle Island, beyond Presqu' Isle. At this latter locality there is every evidence, from the intimate association of the granite and these hornblendic rocks, that they were both liquid, or at least plastic, at the same time. Such a perfect intermingling of the two magmas it seems impossible to explain on any other hypothesis; nor, indeed, are indications of the same intermingling wanting on some of the Picnic Islands.

ACID INTRUSIVES.

General character.—The association of acid rocks of various types with the greenstones of the northern portion of the Marquette area is not less intimate than that already described as occurring at Upper Quinnesec Falls, on the Menominee River. (Chap. III, p. 110.) The general character of these rocks is very similar at both localities, and at both they offer equally valuable material for the study of dynamic metamorphism.

The passage from the Marquette greenstones to the granite lying north of them is an extremely gradual one. There is no such sharp line of contact as is represented on Rominger's map, but, on the contrary, as Rominger himself explains, there is a complete interpenetration of the two rock masses. The granite has intruded itself into the schistose greenstones, for the most part following their bedding and forcing apart their strata. The amount of the acid rock gradually diminishes as we go southward. At the Dead River it still composes over half of the entire mass, but between this and the city of Marquette the dikes and bosses of granite grow less and less frequent. They are,

[1] Geol. Mich., vol. 2, p. 163.

[2] Notes on the Iron and Copper Rocks of Lake Superior. Bull. Mus. Comp. Zool., Harvard Coll. Whole Series, vol. 7, Geol. Series, vol. 1, p. 39.

however, never entirely absent from the northern part of the greenstone area, but extend to the limits of the Eureka series. Around Lighthouse Point and near the Marquette water-works, on the north side of the harbor, bands of reddish and gray acid rocks may be seen along the lake shore in abundance. Some of these are but little altered granites and porphyries, while others are decidedly schistose and seem to owe their structure to dynamic agencies.

Granite.—We will first examine specimens of the unaltered granitic type. These can be nowhere better seen than in the neighborhood of the powder mill on Dead River, near the center of Section 10. Near this place were obtained Nos. 11612 and 11613, both normal granites which penetrate the schistose greenstones. They are of a reddish color and consist principally of feldspar and quartz, both of which are allotriomorphic and form a granular aggregate of interlocking grains. The quartz areas are often composite, and are traversed by lines of fluid-cavities, containing movable bubbles. The feldspar is both monoclinic and triclinic. It is considerably altered to muscovite or kaolin. A little chlorite represents the original presence, in small quantity, of a third constituent, but its condition is now too much altered to allow of its exact determination. The second of the two specimens (No. 11613) is the coarser grained and contains both microcline and pyrite, which are lacking in the former.

No. 11668, also from near the powder mill, occurs where the granite and schistose greenstones are very intimately associated and it seems to be intermediate between them. Under the microscope it appears as a reddish granite, like those last described. Apatite crystals and minute, sharply defined zircons are abundant. The greenish color, which imparts to this rock an appearance intermediate between a granite and a greenstone, is due to the large amount of chlorite present. This sometimes traverses the feldspar in irregular veins and is sometimes massed together in larger areas, as though it had resulted from the alteration of some bisilicate, or, as is still more probable, of a micaceous constituent.

Toward the southern end and on the west side of the Brook section, the banded greenstones and granite are exposed in relations not less interesting than those to be seen at Dead River. A large, glaciated surface of the schists shows intrusions of both granite and diabase which cut directly across the strike. The former rock contains angular fragments of the schist and in one case it fills the inequality formed by the faulting of the schist along a joint plane nearly perpendicular to its bedding. It also forms narrow veins and rows of bulging lenses in the schist. This granite shows no signs of foliation in the field, but a closer study of it in the laboratory discloses the effects of powerful dynamic action. The hand-specimen, No. 11678, proves upon microscopical examination to be an excellent example of peripheral granulation, producing what Törnebohm has called the "mortar-structure." The grains

have rubbed against one another and formed a fine mosaic—mostly a new crystallization—which resembles a cement. The quartz has suffered so much by this process that hardly a trace of the original granitic quartz remains. The feldspar presents rounded grains, often bent or fissured. In the cracks thus formed the same mosaic-like cement is developed. Chlorite, epidote, muscovite, and iron hydroxide are present in this fine grained mass between the rounded feldspars.

No. 11710 was obtained from the rounded knob of gneissoid granite, near the northern end of the Brook section, through which the dike of foliated trap described on p. 145 (No. 11711) passes. In this rock the gneissic structure is quite prominent through a parallel arrangement of the constituent minerals, but under the microscope it quite closely resembles the last specimen. The same peripheral granulation of the original grains by rubbing is even more apparent; and, although there is no marked tendency to parallel arrangement visible in the thin section, the effects of pressure are everywhere shown, as in the undulatory extinction of the quartz, in the production of secondary strain-lamellæ in the feldspar, and in the presence of microcline.

No. 11614 was obtained from a gray granitic knob on the lake shore at the mouth of Dead River. This is penetrated by several sharply defined dikes of fine grained diabase, and, like the rock last described, is decidedly gneissoid in structure. The rock is composed mainly of quartz and orthoclastic feldspar, although both plagioclase and a green fibrous hornblende are also present. The gneissic or "flaser" structure is its most striking feature. This is plainly visible in the thin section and seems to be mainly due to the elongation of the quartz areas in the direction of the foliation. This mineral has suffered greater deformation than the feldspar and is present in long, lenticular patches, whose axes are often sinuous. These are for the most part composite and always show an undulatory extinction. There is, strangely enough, no peripheral granulation visible in this rock.

No. 11660 is from a granite boss on the west side of Pine street, north of Ohio street, Marquette. A fine section has recently been laid open through the center of this mass by some eager gold seeker. The rock is a fresh, even grained aggregate of orthoclase and quartz. Any original micaceous constituent seems to be lacking, although good-sized plates of muscovite have been secondarily developed at the expense of the orthoclase. This feldspar possesses a beautiful zonal structure, which is brought out in unusual distinctness by the different degrees to which the alteration has progressed in different zones. The eruption of this rock must have taken place subsequently to the dynamic movements which metamorphosed so many of the Marquette intrusives. It shows no evidence of pressure in its microscopic structure, although No. 11658, collected but a few feet north of it, from a narrow band of acid rock, shows such evidence in a very marked degree.

Quartz porphyries.—No rocks are better suited to exhibit the effects

of dynamic metamorphism than the quartz porphyries. Some of the more important results which this class of rocks has yielded to European students have already been stated in Chapter I. Near Marquette the narrower of the dikes and intrusions of granitic matter have, in consequence of their rapid cooling, assumed this form. Almost every variety of structure between a typical granite and quartz porphyry may be found by comparing specimens from the different exposures. Furthermore, the various dikes seem to have been subjected to different degrees of mechanical action, so that the successive phases of metamorphism may be traced by a comparative study of them.

In No. 11629 we have a granitoid porphyry which has suffered much from chemical, but very little from mechanical alteration. This was collected from a branching dike of a massive, reddish rock, exposed on the lake shore near the water-works in Marquette. It approaches a granite in being largely composed of porphyritic feldspar crystals, with but comparatively little interstitial groundmass. What there is of this groundmass consists of a fine granular mosaic of quartz and feldspar grains with some sericite. The larger feldspar crystals are colored red by an abundance of fine globulitic dust. They also show an advanced stage of chemical alteration in the development in them of a micaceous mineral (sericite). The only traces of the original biotite consist of chlorite areas dotted over with iron hydroxide. At first glance this rock seems to resemble No. 11678 (above described as a fine example of Törnebohm's mortar structure), but a closer examination shows that the structures, apparently so much alike, must have been produced by very different means. There is in the present instance no evidence of pressure, the feldspar crystals have their original outlines intact, and the interstitial mosaic, instead of being due to a grinding action between the grains, is here evidently a product of the original crystallization.

The next specimen, No. 11620, is a typical quartz porphyry which also has been but little modified by the effects of pressure. It is from a small dike at the eastern extremity of Lighthouse Point and is a much fresher rock than the last. The porphyritic crystals are both smaller and less frequent. They consist of orthoclase, plagioclase, and quartz, imbedded in an abundant microgranitic groundmass. The orthoclase often shows a twinning structure in accordance with the Carlsbad law and is extensively altered to muscovite, large plates of which occur around its crystals. The quartz does not here possess its characteristic dihexahedral form, but occupies oval or irregularly shaped areas which are frequently composite.

These two specimens will serve as representatives of those acid dike-rocks which have been least modified by pressure. They will serve as a starting point for tracing the successive stages of this action in the following specimens. The changes observed are: The deformation and elongation of the quartz crystals; the fracturing and separation of the fragments of feldspars; the parallel arrangement of the new crystalliza-

tion products, giving rise to a gneissic or "flaser" structure; and the development of a cleavage. The intensity of these changes is of course proportionate to the amount of force exerted.

No. 11633, obtained from the quarry on Lighthouse Point (A of map, Pl. VII), is a quartz porphyry which differs only slightly from No. 11620, last described. Its groundmass is somewhat finer grained and sericitic. The porphyritic crystals of feldspar are nearly the same, but the quartzes are deformed and lenticular, sometimes with only an undulatory extinction, sometimes broken into several areas which are more or less displaced from their original position. Although the thin section shows no indications of schistose structure, this in the field is quite pronounced. The rock occurs in the green schist, in small bands, which wedge out very soon. It has a decided tendency to break along planes parallel to the schist-bedding, and upon these planes of parting sericite is abundantly developed.

No. 11653, from the northern edge of Lighthouse Point, just below the Lighthouse, is very similar to the last, except that here a schistose structure is microscopically, as well as macroscopically, visible. The groundmass and porphyritic crystals are quite identical with those above described. In the former there is a brown mica abundantly developed in aggregations of little plates, which form sinuous lines around the porphyritic crystals in a direction parallel to the strike of the surrounding greenstone schists. This fact is mentioned by Dr. Wadsworth, who was the first to discover these rocks.[1]

Nos. 11707 and 11717, were collected from two dikes of porphyry interlaminated with the green schists of the Brook section. In the hand specimens they exhibit no marked foliation, but under the microscope their evidences of mechanical alteration are most interesting and instructive. The groundmass is of the same character as that already described. In it, however, are sinuous bands of green mica which bend and wind about the porphyritic crystals so as to produce a decided "micro-flaser" structure. This feature is more pronounced in the second specimen, although the two are essentially the same. The microscopic appearance of 11707 is represented in Pl. XV, fig. 2. The porphyritic feldspars have suffered little or no change, unless it be by the production of microcline which is quite abundant in the center of some of the crystals of No. 11707. The quartz has suffered much more deformation—a fact which the observations of J. Lehmann[2] and Ch. E. Weiss[3] would indicate to be the rule in rocks of this character. In the present case the quartz is drawn out into long, spindle shaped lenses which are often pinched at their ends into fine lines that bend around the other porphyritic crystals (see Pl. XV, fig. 2). This deformation, however,

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[1] Notes on the Iron and Copper Rocks of Lake Superior. Bull. Mus. Comp. Zool., Harvard Coll. Whole Series, vol. 8, Geol. Series, vol. 1, p. 38.

[2] Untersuchungen über die Entstehung der altkrystallinischen Schiefergesteine. Bonn, 1884.

[3] Zeitschr. Deutsch. geol. Gesell., vol. 29, 1877, p. 418, and Jahrbuch preuss. geol. Landesanstalt für 1883, p. 213. Cf. Rosenbusch: Mikros. Physiog., 2d ed., vol 2, 1887, p. 412.

does not take place without the loss of continuity in the quartz substance. On the contrary a mosaic-like aggregate of interlocking grains is formed whose optical orientation differs more and more in proportion as the original quartz crystal is elongated. In cases where the deformation is slight, only a disturbed extinction results, as may be seen in No. 11753. The presence of interlocking grains of different orientation, as in this instance, would indicate solution and subsequent deposition.

No. 11658, from a narrow acid band immediately north of the granite boss near Pine street, Marquette, is a rock of precisely the same type as those just described but which shows a secondary schistose structure more perfectly developed than any of the preceding. The brownish or greenish mica is here arranged in nearly parallel bands which bend only slightly around what were once porphyritic feldspar crystals. These latter have undergone an almost complete change to muscovite and quartz aggregates, some of which are now drawn out into long lenticular areas. These patches are hardly to be distinguished from the groundmass, except by their coarser grain, and yet they can be traced with certainty back to the original orthoclase. Sharp crystals of pyrite and some epidote are also developed in this rock.

Tuffs of the acid rocks.—Closely allied to these schistose porphyries which occur in dikes are certain banded acid rocks whose most important exposures are along the southern edge of the northern Marquette greenstone area, near the junction of this with the fissile argillaceous shales of the "Eureka series." These are hard, compact, fine grained, but decidedly schistose beds, locally known as novaculite. Indeed, these rocks have been worked to a limited extent as whetstone, whence the name of the small creek flowing through the southern part of Marquette.

The color of these so-called novaculites is sometimes reddish, sometimes pale greenish or yellowish. They are very frequently striped with different shades. Under the microscope they closely resemble the groundmass of the quartz porphyries described in the last section. No porphyritic crystals, however, are ever observed, and the structure is too fine grained to appear schistose in a thin section.

Three essentially identical sections of these rocks were studied from specimens collected at three of the most typical exposures.

No. 11627 is from near Burgess's saw-mill, at the east end of Lake street, Marquette. It has a reddish color produced by an abundance of iron hydroxide scales. The grain is for the most part quite regular, although larger and angular quartz fragments are occasionally seen.

No. 11684 was taken from the glaciated exposure of the novaculites, occurring at the west end of Ridge street, Marquette. A fresh fracture in this rock shows a light gray color. It is parted by intersecting joint systems into sharp rhomboidal prisms which strike slightly south of west. Under the microscope this rock appears as a fine, even mixture of quartz grains and sericite flakes.

No. 11676 was collected at the south end of the "Brook section," near Steinbrecher's house. (B of map, Plate VII.) It is quite similar to the others, but it is much seamed with infiltrated quartz, small veins of which appear in the microscopic section.

The regular banding of these anomalous acid rocks, as well as their interstratification with and gradual passage into the similarly banded greenstone schists, will not admit of the supposition that they were ever eruptive masses, however much we may imagine these to have been metamorphosed. On the other hand, their similarity, in both composition and structure, to the groundmass of the quartz porphyries, is too striking to be overlooked

Apparently only two hypotheses are altogether reconcilable with the observed facts: First, that the rocks are true sediments, like those of the Eureka series, along whose northern edge they lie, which may have been largely derived from disintegrated quartz porphyry material; or second, that they are consolidated acid tuffs which accompanied the eruptions of the porphyries, in the same manner that some of the greenstone schists represent the fragmental diabase material.

Another possible supposition is that these compact, hornstone-like rocks resulted from the contact-metamorphism of preexistent sediments by the diabase eruptions. Such an effect has been extensively produced by the Hartz Mountain diabase, as has been shown by the work of Lossen and others. The resultant rock is known as *adinole*, but it differs essentially from the Marquette novaculite in a constant and high percentage of soda, due to the presence of albite. This, as may be seen from the following analysis, is absent from the Marquette rock. We further have no evidence of the existence of sediments when the greenstones were produced, as all the Huronian beds are younger.

Of the two first mentioned hypotheses, the second is the more probable, first, because of the very constant character of these banded acid rocks, and second, because of their almost exact identity in chemical composition with the massive acid eruptives. The following chemical analysis of specimen No. 11684, from the west end of Ridge street, Marquette, was made by Mr. W. F. Hillebrand:

Silica (SiO_2)	76.99	Potash (K_2O)	3.65
Alumina (Al_2O_3)	13.92	Soda (Na_2O)	0.56
Ferric oxide (Fe_2O_3)	0.45	Lithia (Li_2O)	Trace.
Ferrous oxide (FeO)	0.77	Water (H_2O)	2.35
Manganous oxide (MnO)	Trace.	Phosphorous pentoxide (P_2O_5)	Trace.
Lime (CaO)	0.32		
Magnesia (MgO)	1.12	Total	100.13

It will be seen that this is the composition of an aggregate of quartz and sericite, as the microscope shows our novaculite to be. The sericite is in all probability the result of the alteration of original orthoclase.

The occurrence of similar tuff deposits in connection with eruptive quartz porphyries is well known in Europe, especially in the German

dyas.) They have been carefully studied and described in Saxony,[1] the Vosges Mountains,[2] the Black Forest,[3] and Odenwald.[4] The writer can speak from a very considerable personal acquaintance with the Black Forest and Odenwald tuffs, of their very close resemblance to the Marquette novaculites.

But perhaps the closest analogues of the Marquette tuffs are to be found among those described by Dr. Archibald Geikie, from St. David's, in Wales,[5] a region which, as we shall see in the sequel, presents many points of resemblance to the Marquette district. The analysis of one of them, hereafter quoted (V), agrees very closely with that of our novaculite. Dr. Geikie finds that these acid tuffs accompanied superficial eruptions of quartz porphyries, which were intimately associated with more abundant and contemporaneous extrusions of diabase and diabase tuffs. The acid tuffs have been derived from true fine grained felsites. Some of them are conglomeratic (agglomerates); some of them fine ashy material, which has become consolidated into a sericitic schist. There are various intermediate varieties between the acid and basic types, due to the mingling in different proportions of the two kinds of debris.

Mr. J. S. Diller[6] has also shown that the felsitic rock from Breakheart Hill, near Saugus, Massachusetts, is a silicified quartz porphyry tuff; and from the sharply angular shape of the quartz fragments, of which it is now composed, he concludes that these are pseudomorphs after fragments of an acid glass originally deposited as a volcanic ash.

The following analyses of well characterized acid tuffs from European localities are here quoted on account of their similarity to the Marquette novaculite:

	I.	II.	III.	IV.	V.
Silica (SiO_2)	76.37	79.73	82.47	84.12	80.59
Alumina (Al_2O_3)	13.94	11.34	9.55	9.38	11.29
Ferric oxide (Fe_2O_3)	3.18	0.99	0.43	1.78	0.28
Ferrous oxide (FeO)			0.57		*1.41
Lime (CaO)	....	....	0.53	0.08	0.52
Magnesia (MgO)	....	0.27	trace ...	0.01	0.95
Potash (K_2O)	4.39	3.81	4.69	0.85	2.98
Soda (Na_2O)	1.07	0.17	0.58	0.25	0.72
Water (H_2O)	1.58	2.12	1.18	3.68	†1.96
Total	100.53	98.43	100.00	100.15	100.70

* Manganous oxide trace. † Loss on ignition and water.

[1] C. F. Naumann: Geognosie, 2d ed., vol. 1, p. 671, 1858. Also Erläuterungen zur geol. Specialkarte des kön. Sachsens, Sect. Frohburg (59), Colditz (44), Döbeln (46), Leisnig-Lausigk (43), and Rochlitz (60).

[2] D. Gerhard: Geognistisch-petrographische Mittheilungen aus dem Gebweiler-Thal, 1880. (Cf. Neues Jahrbuch für Mineral., 1881, vol. 1, Referate p. 374).

[3] G. H. Williams: Neues Jahrbuch für Mineral., Beilage-Band 2, pp. 626–634.

[4] Benecke and Cohen: Geogn. Beschr. d. Umgegend von Heidelberg, 1881. pp. 221–235.

[5] On the supposed pre-Cambrian rocks of St. David's. Quart. Jour. Geol. Soc. London, vol. 39, pp. 298–301, 1883.

[6] The felsites and their associated rocks north of Boston. Proc. Bost. Soc. Nat. Hist., vol. 20, pp. 355–368; Bull. Mus. Comp. Zool., Harvard Coll. Whole Series, vol. 7, pp. 165–180; also Science, 1884, vol. 3, p. 653.

I. Thonstein (tuff) from Zeisigwald, near Chemnitz, Saxony.[1]
II. Same.[2]
III. Silicified tuff, Oelberg, near Schriesheim, Odenwald.[3]
IV. Silicified tuff, Kesselberg, near Triberg, Black Forest.[4]
V. Felsitic tuff breccia, Clegyr Hill, St. David's, Wales.[5]

If, then, these banded acid rocks occurring near Marquette, as seems most probable, really do represent solidified tuff material of the quartz porphyries, we might expect to find transitional forms, grading into the banded green schists. These do appear to exist, and indicate that some, at least, of the eruptions of both acid and basic rocks were nearly contemporaneous.

BANDED GREENSTONE SCHISTS.

The banded greenstone schists which form the prevailing rock over the northern portion of the Marquette area have been regarded by all geologists who have ever studied them as originally sedimentary deposits, and a repeated examination of them in the field seems incapable of leading to any other conclusion. They are everywhere stratified with the greatest regularity in bands of lighter and darker shades of green. This structure is to be most advantageously seen in the woods just north of Marquette and near Lighthouse Point. Here glaciated areas of considerable extent often show a finely ribboned appearance, looking as though the sharp, parallel lines had been drawn with a ruler. The alternation in the color and composition of the layers is so frequent and so constant, and their parallelism to the east and west strike of all the rocks of this neighborhood is so exact that no hypothesis of their originally massive character will satisfactorily account for the observed facts.

On the other hand, the chemical and the microscopical characters of these schists agree closely with those of associated massive greenstones which are known to have been derived by the alteration of basic eruptive rocks. Both are composed of fibrous green hornblende, quartz, epidote, zoisite, and chlorite. There must, therefore, have been a close similarity in the original composition of these two classes of rocks, in spite of the wide difference in their structure.

Prof. M. E. Wadsworth, who has ably advocated the eruptive origin of many of the rocks occurring near Marquette, regards these banded schists as undoubtedly of sedimentary origin. He says:[6]

> The schist from the same specimen (45) is composed of quartz, argillaceous material, chlorite, hornblende, magnetite, "leucoxene," and a little augite. It would seem that this had been formed from detrital material of the same nature as the dikes (basaltic). The close resemblance of the "diorite" and schist in mineralogical characters, but not in structure, is shown in another section containing the junction of the two rocks (48).

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[1] Neues Jahrbuch für Mineral., 1864.
[2] Ibid., 1859.
[3] Die zur Dyas gehörigen Gesteine des südlichen Odenwaldes, von E. Cohen, 1871, p. 57.
[4] Neues Jahrbuch für Mineral., Beilage-Band 2, p. 630.
[5] Quart. Jour. Geol. Soc. London, vol. 39, 1883, p. 297.
[6] Notes on the Iron and Copper Districts of Lake Superior. Bull. Mus. Comp. Zool., Harvard Coll., Whole Series, vol. 7, Geol. Series, vol. 1, p. 37.

Specimes of these banded greenstone schists which were collected from different localities within the northern Marquette area, although they are macroscopically nearly identical, present a great variety in their microscopical structure.

Nos. 11618 and 11619, from Lighthouse Point, Marquette, are comparatively coarse grained rocks composed largely of a green fibrous hornblende. The structure of this mineral, especially in No. 11619, is unusual. What at first glance looks like a confused mass of irregular and ragged hornblende areas, when more carefully examined, is found to consist of more or less radiating bundles of hornblende fibers, resembling sheaves. The center of these bundles is their most compact portion. Here the hornblende substance is often continuous and homogeneous, but toward the two ends of the mass it appears to be frayed out into separate fibers. These are so regularly divergent in their arrangement as to produce a black brush which sweeps across them as the stage of the microscope is revolved between crossed Nicol prisms. This peculiar, sheaf-like grouping of the hornblende is shown in Pl. XVI, Fig. 1. It is very similar to that described by de la Vallée-Poussin and Renard in an amphibolite occurring near Laifour, in the valley of the Meuse,[1] and by Renard in the metamorphosed Devonian slates of Bastogne in the Ardennes Mountains.[2] Though it can still be traced in specimen No. 11618, this structure is by no means as distinct as in the case just described.

The groundmass in which this hornblende lies is a finely granular aggregate of albite, or quartz and albite grains. In it occur some chlorite, epidote, or zoisite in good sized individuals, and, at least in No. 11619, some small ilmenite particles, surrounded by a highly refractive leucoxene border. There is comparatively little groundmass in either of these specimens, but of the two No. 11618 contains the more.

Nos. 11730, from the western part of Marquette, between Michigan and Ohio streets, and 11734, from the corner of Front and Ohio streets, are both banded greenstones of the same type as the specimens last described. The former contains less hornblende, though this mineral, is, nevertheless, abundant in the same sheaf-like bundles as before. The groundmass is a fine grained albite mosaic, which contains some quartz and some epidote. The latter specimen, No. 11734, is largely composed of an unusually dark green and pleochroic hornblende, in confused ragged and fibrous groups. Along certain lines, where this component is less abundant, the rock assumes a lighter shade. The albite mosaic is present, but not to the exclusion of areas of gray saussurite, which sometimes show indications of a lath-like form, like that of the diabase feldspars. Narrow seams filled with epidote, or an aggregate of albite and epidote, traverse this rock parallel to its banding. Ilmenite grains, with their rims of leucoxene, occur in each of these specimens.

[1] Mém. sur les char. min. et strat. des roches dites plutoniennes, etc., Brussels, 1876, p. 252, Pl. V, Fig. 25.

[2] Les roches grénatifères et amphiboliques de la région de Bastogne. Bull. Mus. roy. d'hist. nat. de Belgique, 1882.

There is nothing in the microscopical structure of these slides to suggest a massive eruptive rock; on the contrary, the two instances cited, where a similar sheaf like hornblende has before been noticed, are cases of supposed metamorphosed tuffs.

No. 11630, from the quarry on Lighthouse Point (A of map, Pl. VII) is also largely composed of hornblende in pale green, ragged-looking individuals, but without any of the sheaf-like structure. Amid the hornblende a clear transparent feldspar, evidently albite, has been abundantly developed in good-sized grains, which show a sharp twinning striation. The gradation of this well characterized albite into the granular mosaic lends additional force to the supposition that this also is composed of the same mineral, as, indeed, Lossen has shown to be the case in many of the regionally metamorphosed diabases of the eastern Hartz.[1]

Nos. 11631 and 11637 are other specimens of the banded greenstone schists from the same quarry as the last on Lighthouse Point. The former is, perhaps, the most typical, although an abundance of calcite shows that it is much weathered. Its alternating light and dark green bands are due to the fact that hornblende is still present in the latter, while its place is supplied in the lighter colored bands by a pale chlorite and epidote. An opaque iron oxide, often surrounded by a leucoxene rim, is found in small particles scattered through this rock, as is also a little biotite. The second of the above mentioned specimens, No. 11637, which was taken from just beside the great dike, shows what the last described rock was when it was in a fresher condition. The calcite is here absent, and the rock is, for the most part, a mass of ragged and raveled hornblende. Among this is scattered some clear, transparent feldspar (probably albite) and zoisite, or epidote, which occurs in irregular crystalloids, arranged in long, parallel lines. The iron mineral and biotite are present as before.

No. 11623, found beside the great dike on Lighthouse Point, is only a confused aggregate of very pale and very fibrous hornblende needles with calcite. Lighter bands are occasioned in this rock by a preponderance of calcite and chlorite over the hornblende.

No. 11626 is a gray schistose rock from the exposure near Burgess's saw-mill, on Lake street, Marquette. It is full of calcite, which is arranged in bands along with a very finely granular mosaic. Hardly any hornblende is visible in this specimen, but veins of epidote and some chlorite occur in it.

Along the deep north and south exposure of the greenstone schists which has been described as the Brook section, these banded greenstones are also very admirably displayed. For the most part they are quite like those occurring in the neighborhood of Marquette. In one particular, however, some of them present an unusual feature which it is not altogether easy to explain. This consists in the presence of len-

[1] Zeitschr. Deutsch. geol. Gesell., vol. 24, 1872, p. 730. Jahrbuch preuss. geol. Landesanstalt für 1883, p. 640; ibid., für 1884, p. 528. Erläut. zur geol. Specialkarte von Pr., Blatt Wippra, Berlin, 1883.

ticular masses of a white feldspathic substance, which are so elongated in the direction of the bedding that while they generally present a lens-shaped form, their cross-section is nearly circular. The size of these lenses, which externally resemble what the Germans call "Augen" or eyes, is extremely variable. Some are smaller than peas, while others are more than two inches in length. The extent also to which they are elongated differs very much in different cases. Some are represented only by narrow white lines which are occasionally thickened or swelled out into oval spots. Between these and such as vary comparatively little from a spherical form we may find all intermediate stages.

These white lenses are by no means universally distributed through the green-schists of the Brook section; on the contrary they occur only rarely in bands which transverse the greenstones parallel to their bedding. One of these bands consisted of only a few rows of large, oval masses, exactly resembling rounded pebbles, but in spite of its narrowness it could be traced for a considerable distance.

The white color of these lenses or "Augen" presents a decided contrast to the dark green of the inclosing schists. Their outline, too, is quite sharp, and yet, upon a close examination, they are seen to pass gradually into the substance of the surrounding rock. What their origin was, whether they were inclusions much flattened by subsequent pressure, or secretions of the rock itself, or infiltrations, it now seems difficult, if not impossible, to decide.

Sections 11703 to 11705*a*, show the microscopic composition and structure of these lenticular masses as well as their relation to the inclosing rock. This latter is in all cases a typical hornblende schist or amphibolite. It is composed of small, compact needles of strongly pleochroic, green hornblende, colorless grains of feldspar and probably quartz, and the minute, highly refractive epidote particles so characteristic of the crystalline schists. The feldspar is very fresh and free from inclusions, as though it were the product of a new crystallization. It rarely possesses an albite or microcline twinning structure, but for the most part it is so homogeneous and limpid that it closely resembles quartz. Lossen has called particular attention to the difficulty of distinguishing a mosaic of secondary albite from quartz under the microscope,[1] and it is very possible that quartz grains are actually present in this rock, although in certain favorable cases a biaxial character was substantiated.

No. 11703 is cut in the direction of the bedding and shows the hornblende in strictly parallel arrangement. Its feldspar "Augen" are very much elongated, while in No. 11705, which is cut nearly perpendicular to the bedding, they are as broad as they are long. This substance was undoubtedly once some triclinic feldspar, but this has been changed to saussurite which now consists of epidote and sericite imbedded in a

[1] Zeitschr. Deutsch. geol. Gesell., vol. 31, 1879, p. 441, et seq. Jahrbuch preuss. geol. Landesanstalt für 1884, pp. 528, 544, Pl. XXIX, fig. 4.

new crystallization of albite. They contain no hornblende, but there seems to be a condensation of this mineral in the schist around their edge and enough of it penetrates for a distance into their substance to form a gradual transition rather than a sharp line of contact between them and the inclosing rock.

The composition of these "Augen" is not in every instance the same, although they all appear to have been derived from some form of feldspar. In No. 11704 they are composed wholly of epidote, while in No. 11705*a* the original feldspar was more acid and sericite has been produced almost to the exclusion of epidote.

Other of the banded greenstones collected along the Brook section are quite devoid of the white "Augen" and agree closely with the rocks around Marquette.

Nos. 11706, 11713, and 11718 are essentially hornblende rocks, containing some altered feldspar and some quartz. They are plainly banded, the alternate layers differing in both color and composition.

No. 11671, from an exposure very near the center of section 17, consists of sharp epidote needles and a little quartz, imbedded in a confused mass of pale green, fibrous hornblende.

Nos. 11610, 11611, and 11667, from near the powder mill on Dead River, are all schistose greenstones in a much altered condition consisting now of chlorite, quartz, and carbonates.

As has been already remarked, the structure of these greenstone-schists is such as to necessitate a belief in the original nature of their stratification; while, on the other hand, their chemical as well as their mineralogical composition renders it impossible to separate them from the massive and highly altered greenstones (uralite diabases, etc.), with which they are most intimately associated. Their parallel banding indicates a fragmental, but their chemical and their mineral composition indicate an igneous origin. The only satisfactory reconciliation of these opposite sets of characters is to be found in that group of rocks intermediate between sediments and lavas, known as volcanic tuffs.

In the opinion of the writer, then, the banded greenstone schists of the northern Marquette area are to be regarded as consolidated and highly metamorphosed *diabase tuffs*. These are intimately associated with numerous contemporaneous flows of diabase and quartz porphyry, together with tuffs of the latter rock; while all have been broken through by much younger dikes, both basic and acidic.

From the preceding petrographical descriptions it will be seen how great is the similarity between the banded greenstones of Marquette and the older massive diabases. Mineralogically, they are now identical, but the fine parallel banding of the former necessitates the assumption that their origin differed from that of the eruptives.

In a former paper[1] the writer has maintained that two geological

[1] Bull. U. S. Geol. Survey, No. 28, p. 1.

masses as different in their structure and origin as a clay-bank and a lava-stream, *if they possessed the same chemical composition to start with*, when subjected for a long period to exactly the same physical conditions, would result in the same products. This is, of course, true only when these conditions allow of profound metasomatic and structural changes. On the other hand, when we find two intimately associated rocks which for a long time have been subjected to exactly the same conditions, but which still bear evidence of dissimilar origin, in spite of practical identity of mineral and chemical composition, we may safely consider them as originally of the same, or of similar chemical composition. Now, it is difficult to imagine any stratified sediments of the composition of diabase, except diabase ashes; nor could these have undergone transportation by water without suffering important chemical changes. We therefore conclude that the banded schists represent volcanic debris deposited at or near the point of its origin.

In order to obtain a clear idea of just how these ancient and much disguised tuffs acquired their present form and apparently dual character, it will be advantageous to ascertain what is known of analagous formations of comparatively recent date. Capt. C. E. Dutton's descriptions[1] of the fragmental rocks accompanying the Tertiary eruptives of the high plateaus of Utah, are well suited to this purpose. He says, in speaking of the extent of these deposits:[2]

Some of the most interesting lithological problems presented by the volcanic products of the high plateaus are those relating to the origin and development of what may be termed the clastic igneous rocks, or rocks apparently composed of fragmental materials of igneous or volcanic origin, but now stratified either as so-called tufaceous deposits or as conglomerates. These are exceedingly abundant in all of the great volcanic districts of the world, and often enormously voluminous. How those of the high plateaus would compare, in respect to magnitude, with those of other regions, I do not accurately know, but absolutely their bulk is a source of utter astonishment. They cover nearly 2,000 square miles of area, and their thickness ranges from a few hundred feet to nearly 2,500 feet, the average being probably more than 1,200 feet. Lavas are frequently intercalated, but much more frequently no intercalary lavas are seen, and in general they seldom for·· any large proportion of the entire bulk when they occur in conjunction with the clastic masses.

Again, in speaking of the peculiar liability of such deposits to metamorphism, the same writer says:[3]

A very striking characteristic of these clastic volcanic rocks, both the tufas and the conglomerates, is their great susceptibility to metamorphism. Not only have the beds in many localities been thoroughly consolidated, but they have undergone crystallization. Those tufas and conglomerates which are of older date, and which have been buried beneath more recent accumulations to considerable depths, rarely fail to show conspicuous traces of alteration, and in many cases have been so profoundly modified that for a considerable time there was doubt as to their true character. The general tendency of this process is to convert the fragmental strata into rocks having a petrographic facies and texture very closely resembling certain groups of igneous rocks. When we examine the rocks in situ no doubt can exist for a moment that

[1] Report on the Geology of the High Plateaus of Utah. By C. E. Dutton; Washington, 1880.
[2] Ibid., p. 69.
[3] Ibid., pp. 79, 80.

they are water-laid strata. The hand-specimens taken from the beds, which are extremely metamorphosed, might readily pass, even upon close inspection, for pieces of massive eruptive rocks were it not that the original fragments are still distinguishable, partly by slight differences of color, partly by slight differences in the degree of coarseness of texture. But the matrix has become very similar to the included fragments, holding the same kinds of crystals, and under the microscope it shows a groundmass of the same texture and composition. * * *

I see nothing at all incredible in the idea of metamorphism producing rocks so closely resembling some eruptive rocks that they can not be petrographically distinguished from them. It seems rather that we ought to anticipate just such a result from the alteration and consolidation of pyroclastic strata. The materials which compose them consisted originally of disintegrated feldspar, pyroxene, and the matter which constitutes the amorphous base of all eruptive rocks.

We are thus enabled to see that there is, at least, no geological difficulty in the explanation here offered of the origin and nature of the banded green-schists at Marquette. On the high plateaus of Utah, which form one of many similar districts, conditions are plainly seen to have prevailed quite similar to those here assumed for the more ancient rocks of Lake Superior; and yet the metamorphism which has taken place in the ancient Archean deposits is hardly greater than that described by Captain Dutton in the tertiary tuffs.

The most generally accepted type of diabase tuffs is the German "Schalstein;" but, as Rosenbusch well remarks,[1] in the course of many years so many totally different rocks, with only the most superficial resemblance to each other, have been described under this designation, that there is now no definite meaning whatever which can be attached to this term. The schalsteins are for the most part, green or greenish in color, earthy and schistose; but among them have been included altered and foliated diabases on the one hand, and true sediments on the other, while some of them are undoubtedly true diabase tuffs. In Germany their distribution is very wide in Nassau, Saxony, and Bavaria.

The microscopic sections of German Schalsteins accessible to me for comparison were those in the Stürtz collection of typical rocks belonging to the petrographical laboratory of the Johns Hopkins University. They are from the localities of Rübeland in the Hartz Mountains, and Diez, Baldinnstein, Dillenburg, and Weilburg in Nassau. In spite of extreme alteration, resulting in several cases in the survival of only chlorite, calcite, and iron oxide, it can be distinctly seen that the specimens were originally totally different. The rocks from Diez, Dillenburg, and two out of the three labeled Weilburg, are only very amygdaloidal diabases. The structure in the base is well preserved, while the amygdules are filled with calcite surrounded by a rim of chlorite. The rock from Rübeland is apparently of the same nature, but the original structure has now disappeared. In the specimen from Baldinnstein and in one from Weilburg there is no indication of diabase structure, but there is a spheroidal aggregation resembling that seen in palagonite.

[1] Mikros. Physiog., 2d ed., vol. 2, p. 245.

The most extended descriptions of these rocks have been given by Gümbel, who has treated the schalsteins of the Fichtelgebirge in Bavaria in a most careful manner.[1] Rothpletz has described the tuffs and agglomerates associated with the Silurian diabases in Saxony.[2] In Great Britain the ancient volcanic areas of Cornwall and St. David's in Wales show the closest similarity, both in the character of their rocks and in certain features of their structure to the Marquette region. The slaty blue "elvans" of the former district were regarded by De la Beche as altered ash-beds.[3] J. Arthur Phillips arrived at the same conclusion.[4] He says:

The Cornish rocks afford numerous examples of ancient lava flows so interbedded with slates and schists of the district as to lead irresistibly to the conclusion that they are contemporaneous igneous deposits.

Also again:[5]

The slaty blue elvans found between St. Erth and St. Stephens (in Bramwell) have a chemical composition identical with that of the altered dolerites, and may be, as was formerly suggested, highly metamorphosed ash-beds.

The basic tuffs, like the acid ones, occurring at St. David's have been described by Dr. A. Geikie.[6] He finds that all varieties of texture can be traced, from large grained breccias to fine schistose mudstones. The finer material includes angular, subangular, and rounded blocks or lapilli, consisting not alone of diabase, but also of the more acid felsitic rocks. These are true agglomerates, and their striking resemblance to certain other of the schistose greenstones of the Marquette belt will be alluded to in the sequel.

The eruptive rocks which Dr. Hans Reusch has recently studied in the regionally or dynamically metamorphosed district on the west coast of Norway, present a close resemblance to those occurring near Marquette.[7] He finds diorites, in part very schistose, which have originated through the metamorphism (uralitization and epidotization) of ancient

[1] Geognostische Beschreibung des Fichtelgebirges, mit dem Frankenwald und dem westlichen Vorlande, Gotha, 1879, pp. 222 et seq.

[2] Erl. zur geol. Specialk. Sachsens, Sect. Frankenberg-Hainichen (78), pp. 16 and 21; Sect. Schellenberg-Floha (97), p. 65.

[3] Geological Observer.

[4] Quart. Jour. Geol. Soc. London, vol. 34, p. 493.

[5] Ibid, p. 495.

[6] Quart. Jour. Geol. Soc. London, vol. 39, p. 297, 1883.

[7] Geologische Beobachtungen in einem regional-metamorphosirten Gebiet am Hardangerfjord in Norwegen, Neues Jahrbuch für Mineral., Beilage-Band 5, pp. 52-67. On pages 54, 55 the author says: Nicht selten zeigt das dioritische Gestein einen schichtenweisen Wechsel von verschiedenen Varietäten. In diesem Falle bin ich geneigt, anzunehmen, dass das ursprüngliche Gestein nach Art der Tuffe gebildet wurde. Dies geschichtete dioritische Gestein bildet einen Uebergang zu den grünlichen feinkörnigen oder dichten, geschichteten, mehr oder weniger schieferigen Gesteinsarten, welche die Hauptmasse von dem ausmachen, was ich für basische Tuffe halte. Diese Gesteine führen als wesentliche Bestandtheile Hornblende, Chlorit und Epidot, daneben gern reichlich Carbonspath. Sie entsprechen einigermassen den Schalsteinen der deutschen Petrographen. Eingelagert kommen Massen vor, die man am ehesten für geflossene Ströme halten muss. Einige sind wohl auch intrusive Gänge. Uebrigens ist es hier, wie anderswo unter ähnlichen Verhältnissen, oft schwierig zu unterscheiden was massig erstarrt und was klastische Bildung ist. For the detailed descriptions of these rocks by Dr. Reusch, see "Bommelöen og Karmöen," Christiania, 1888 (in Danish), p. 112, and the appended English summary of contents, p. 402.

gabbros. These are most intimately associated with granites and quartz porphyries, while both acid and basic rocks are accompanied by abundant tuff deposits.

In America hardly anything reliable has been published on basic tuffs. Edward Hitchcock speaks of diabase tuffs in the trias of Massachusetts, but gives nothing specific respecting their nature.[1] References to this class of deposits are scattered through the writings of some of the Canadian geologists, especially in the recent report of Mr. A. C. Lawson on the Lake of the Woods region.[2]

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[1] Geology of Massachusetts, 4°, 1841, p. 648.

[2] Geol. and Nat. Hist. Survey Canada, Ann. Rept. for 1885, Rept. CC., 1886.

CHAPTER V.

GREENSTONE BELTS OF THE MARQUETTE DISTRICT—Continued.

ROCKS OF THE SOUTHERN PORTION OF THE MARQUETTE AREA.

On the south side of the narrow band of Huronian slates which has been designated as the "Eureka Series," the greenstones of the Marquette area present a decided contrast to those which have been described in the previous section as occurring on its north side. They are, for the most part, massive, pale green in color, and apparently homogeneous in structure. Only in rare instances can individual minerals be detected with the unaided eye. A schistose structure is not uncommon in these rocks, but it is evidently a pressure foliation, while the parallel banding or striping, so frequent in the greenstones of the northern area, is altogether absent. A study of these pale green aphanitic greenstones seems to indicate that they were not originally to any great extent tuff deposits, but massive flows of diabase, which have since suffered profound chemical and structural change in consequence of having been subjected to intense dynamical action.

In addition to their foliation, they are fractured and brecciated in various degrees, and often exhibit a curious spheroidal or lenticular parting, for which no perfectly satisfactory explanation has been found.

The monotony of these prevailing aphanitic greenstones is interrupted by bands of more coarsely crystalline and less altered rocks, which represent basic dikes of more recent origin.

THE APHANITIC GREENSTONES.

The general character of these widely distributed rocks as seen under the microscope, is shown in Pl. X, fig. 2, drawn from a specimen collected near the town of Negaunee, where this type is developed even better than near Marquette. In the mass which appears to the unaided eye as quite homogeneous, the microscope discloses long, almost acicular feldspar crystals, embedded in a confused aggregate of hornblende needles, chlorite scales, epidote, quartz, calcite, and cloudy spots, probably derived from leucoxene. The feldspar in these rocks is, as a rule, fresh, and their twinning lamellæ are still distinctly visible. Some of the more acicular crystals seem divided at the ends, as is so often the case in semi-vitreous surface rocks whose feldspar microliths are not completely formed. Indeed, in many of their characters, these aphanitic greenstones strongly resemble porphyrites or melaphyres

whose glassy base has been completely transformed into an aggregate of secondary products. Their structure, imperfectly preserved as it is, strongly indicates a superficial origin.

As typical representatives of these homogeneous pale green rocks may be mentioned: No. 11638, from the mouth of Whetstone Brook, just south of Marquette; Nos. 11725 and 11726, from the summit of the hill immediately south of the last locality; No. 11694, collected about an eighth of a mile south of the State road on the line between the southeast and southwest quarters of Sec. 27, T. 48 N., R. 25 W.; and No. 11721, from south of the township road, on the line between Secs. 27 and 28, T. 48 N., R. 25 W.

These aphanitic greenstones appear to have been particularly sensitive to dynamic action. We find locally developed in them every degree of pressure foliation from a coarse, slickensided breccia to a chloritic slate. The cleavage, however, is developed parallel to a line rather than parallel to a plane, as is the case with a true bedding. There is a tendency to break into rhomboidal prisms or along almost any plane which is parallel to the average direction of dip.

No. 11696 is a much gashed and brecciated greenstone which adjoins on the north an uralite diabase dike, No. 11695 (see p. 169). It is both schistose and chloritic, but its microscopical structure shows plainly that it was once a diabase, and that its present character is due entirely to the action of some great mechanical force. The typical ophitic structure or irregular network of lath-shaped feldspar crystals is still readily discernible. The mechanical action seems to have been rather a stretching than a compression. The feldspar crystals, which are considerably altered, are broken and the fragments pulled apart. The secondary chlorite, so common in all stretched rocks (cf. Pl. XI, fig. 2), is here abundant in the numerous longitudinal cracks, which traverse the rock irrespective of its component minerals. This is always arranged with its scales or fibers perpendicular to the walls of the fissure.

In addition to such brecciated rocks as the last specimen, very perfectly schistose varieties of these aphanitic greenstones are common in the southern part of the Marquette area, their strike conforming to that of all the other rocks of this region. These are typically exposed at the mouth of Whetstone Brook (Nos. 11639 to 11643); in the railroad cutting just west of it (No. 11645); on the high hill still farther westward (No. 11726); and in the Duluth, South Shore and Atlantic Railroad cutting just north of the Marquette sandstone quarries (No. 11691).

For the most part, these rocks are a fine chloritic mass, which, under the microscope, shows a pronounced schistose structure, but only rarely any certain indications of eruptive origin. Very faint but unmistakable traces of the ophitic structure are nevertheless sometimes visible even in these rocks, as, for instance, in No. 11726, which was entered in the field notes as a "slaty band traversing the massive greenstones above Whetstone Brook."

The history of these schistose greenstones must be deciphered with the conjoint evidence afforded by the microscope and a study of their relations in the field. The occasional survival of the characteristic diabase structure even in some of the more foliated forms, taken in connection with their evident identity with and gradual transition into the massive varieties, appears to be sufficient proof that, with the exception of certain unimportant tuff deposits, these green schists have been derived from basic eruptives through the agency of intense mechanical and chemical action.

The closest analogy to the rocks of the southern Marquette greenstone area is to be found in the metamorphosed diabases of the eastern Hartz. These rocks have been minutely studied and for the first time successfully deciphered by K. A. Lossen, of Berlin. His descriptions could be applied almost verbatim to the Marquette greenstones; and each of these two similar areas can but have additional light thrown upon its interpretation by the facts afforded by the other.[1] Lossen distinguishes between the coarse grained or granular (körnig) and the fine grained (aphanitisch) diabase, as has been done in the area here under discussion. He finds that both rocks, but especially the aphanitic type, are very sensitive to dynamic action, and that in the process of mountain making they have been to a large extent passively metamorphosed and converted into breccias, "Flaser" diabase and green schists. The last named "grüne Schiefer" are of particular interest to us on account of their resemblance to the schistose rocks of the southern Marquette area. In the Hartz they make a conformable member of the Wieder schists (hercynian) which are of very considerable extent and are always associated with the aphanitic diabase. The minute and careful studies of Lossen have led him to the conclusion that these schists are not in any way sediments nor even diabase tuffs ("Schalsteine"), but molecularly metamorphosed eruptive rocks, of a fine grained diabase type.[2] The more massive rocks are considered to represent old lava flows which occurred while the accompanying sediments were being deposited, and the idea that the green schists of the Wieder horizon were once also massive diabases, is based both upon the field relations of these rocks and more especially upon the frequent remains of the diabase structure which they still contain.

The published descriptions of many other green schist areas in Europe—notably in Bavaria, Saxony and the Taunus—show that they possess a strong resemblance to those of Michigan and the Eastern Hartz, and it is not improbable that they also may have had a similar origin.

[1] The descriptions of Lossen are contained in the explanations to the special geological map of Prussia and Thuringia (Erläuterungen zur geologischen Specialkarte von Preussen und den thüringischen Staaten) sheets Pansfelde (1882), and Wippra (1883).

[2] "Die mikroskopische Untersuchung characteristischer Vorkommen dieser typischen Diabasaphaniten vergesellschafteten grünen Schiefer hat ergeben, dass sie, wenn nicht insgesammt, doch grossentheils als *unter Druckschieferung molecular umgewandelte Diabase* aufzufassen sind." Ibid., Bl. Wippra, p. 27; (cf. also p. 46 and Bl. Pansfelde, p. 52).

A noteworthy feature of the aphanitic greenstones and greenstone schists of the southern Marquette area, and one which is exhibited in a still more marked degree by the similar rocks occurring near the town of Negaunee (see the following section), is their frequent division into spheroidal, ovoid, lenticular or more irregularly shaped masses. These differ very much in size, as well as form, and often show a tendency to fit together like stones in a mosaic, although they are always separated by interlacing bands of a softer, more schistose and generally darker material. These anastomosing bands seem to wind about the harder and more massive cores, becoming thinner or thicker according as the masses approach each other more closely, or are more widely separated by the rounding off of their corners. This peculiar structure, which appears to be only local in its development, may be seen at the mouth of Whetstone Brook in Marquette, near Baldwin's kilns, near Negaunee (NE $\frac{1}{4}$ of NW $\frac{1}{4}$ of Sec. 28 W., T. 48 N., R. 26 W.), and on the south side of the Carp River along the logging road leading northward from the east end of Teal Lake. The accompanying diagram (Fig. 26), drawn from the last named exposure, illustrates the general character of this structure.

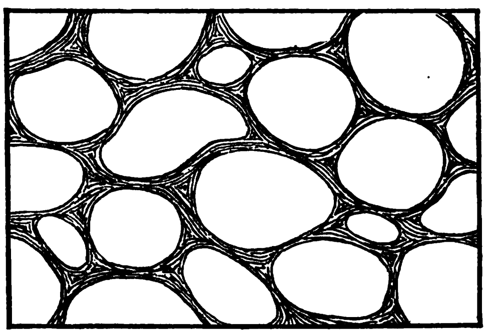

FIG. 26.—Diagram to illustrate spheroidal parting in aphanitic greenstone. Carp River. Scale, 3 feet to the inch.

The cores generally seem to be quite massive, but in some cases they have a latent foliation which is developed by weathering. Where the rock has become decidedly schistose, as was observed in one part of the Carp River exposure, these cores are pulled out into long interlocking lenses, which have their longest axes parallel to the foliation. (See Fig. 27, p. 177.)

Such a structure as that above described appears to be not uncommon in the greenstones and greenstone schists of the Northwest. It is well known to the Canadian geologists, who have designated the rocks exhibiting it as "concretionary traps." It is described by Dr. Andrew C. Lawson, in his report on the Lake of the Woods, in the following terms:

This structure consists of the rock being divided into more or less irregularly spherical or ovoid masses, varying in diameter from 2 to 3 inches to as many feet. These ovoid masses are not in close contact, but are separated from one another by an in-

terstitial material. The concretionary masses are at their points of nearest approximation to each other, generally about half an inch or an inch apart, no matter what may be their size, so that when the ovoid masses are large, the interstitial material appears in section as thin, anastomosing sheets, in which is developed a schistosity parallel to the ontlines of the ovoid masses they inclose. The interstitial filling is generally of a darker color, more chloritic, softer, and of a finer, more homogeneous texture than the ovoid masses, and weathers out, often leaving the latter, in sections afforded by glaciated surfaces, surrounded by sharp little trenches.

The ovoid masses are uniformly arranged as regards the direction of their long axes, and each one is surrounded by a sharp border half an inch wide, of a dark greenish gray color, which has been more resistant to weathering agencies than the rest of the rock. The ovoid masses present as the result of weathering a rough or pimpled surface of porous aspect and bleached greenish white color. The interstitial filling is firmer in texture and softer than either the ovoid masses or their border, and is intermediate between them in color, with a brownish yellow tinge.

In the hornblende schists this ovoid structure in the rock takes a somewhat different aspect, and presents the appearance of thin anastomosing sheets of dark green, soft chloritic material, sometimes enveloping completely ovoid or irregularly shaped portions of the hornblende schist, and at others losing themselves in a tapering, disconnected fashion in the main mass of the rock.[1]

It is evident upon the most superficial examination that this structure is in no way "concretionary," as that term is commonly understood. Nor is it possible to suppose that the harder ovoid masses were originally ejected fragments, which have become imbedded in a finer matrix of volcanic material forming a true agglomerate. A sufficient objection to this hypothesis is the fact that these harder masses so frequently fit together like parts of a mosaic.

In many instances the spherical or ovoid form of the disjointed fragments is so perfect that the structure strongly resembles the spheroidal parting, developed in a latent form in eruptive rocks by cooling, and made more distinct by weathering. This, which is really a perlitic structure on a large scale, frequently extends through large masses of eruptive material; and the descriptions and photographs kindly furnished the writer by Mr. Whitman Cross, who has studied it in Colorado, indicate many points of striking resemblance to the structure of the Lake Superior greenstones. It is quite possible that the phenomenon may in certain cases be due to contraction, although in others the irregular shape of the fragments, as well as their occurrence in fragmental rocks, indicates another origin.

A structure showing many points of resemblance to that here described is presented by the well known green schists (grüne Schiefer), occurring near Hainichen, in Saxony, and the explanation afforded by the study of their very favorable exposures may assist our understanding of the parting in the Lake Superior greenstones. The fragments of the Saxon green schists, in spite of the great difference in their size (varying from that of a pea to that of a house), are so rounded that they were formerly regarded by C. F. Naumann as a conglomerate.[2] Never-

[1] Geol. and Nat. History Survey of Canada, Annual Report for 1885 (new series, Vol. 1); Report CC on the Lake of the Woods, by A. C. Lawson, pp. 52, 53.

[2] Erläuterungen zur geogn. Karte des Königreichs Sachsen, pt. 1, 1834, p. 69.

theless their fitting together convinced subsequent observers that the structure must be due to brecciation in situ.[1] These rocks have more recently been carefully studied by A. Rothpletz, who was able to trace the structure downward into a series of interlacing joints, and who explains the rounded character of the fragments and the production of much of the interstitial material by the rubbing together, under the action of intense orographic pressure, of a mass already finely subdivided by cracks. Fig. 4 of Rothpletz's plate gives a fair representation of some of the Lake Superior occurrences.[2]

The hypothesis of the mechanical origin of this curious parting in the greenstones and greenstone schists seems best to explain the following facts:

(1) Its occurrence in fragmental rocks.

(2) The often very irregular shape of the fragments.

(3) The interlocking of the same into a mosaic.

(4) The fact, noticed by Lawson, that the thickness of the interstitial layer is independent of the size of the fragments.

(5) The fact, also noticed by the same observer, that the interstitial layer in horneblende schists often loses itself in the rock without completely surrounding a fragment.

(6) The identity in petrographical character of all the cores in the same mass.

(7) The similarity, except where it is more altered, of the interstitial material to that forming the ovoid cores. At the Carp River locality (see p. 176) the cores contain small white feldspar crystals, which are also present in the layers which separate them.

COARSE GRAINED DIKE ROCKS.

The fine grained aphanitic greenstones and greenstone schists which prevail over the southern Marquette area are intersected by many bands of coarser material whose eruptive character is still evident in their microscopic structure. These represent later dikes of a basic character which have broken through the older rocks, and which on account of their more recent eruption are less altered. One of the most typical of these is exposed on the small island near the end of the Cleveland ore dock in Marquette. This small island consists of two portions connected by a narrow neck. The southern part is composed of a hard, compact, brown rock, which is sometimes quite coarse grained or porphyritic. Its color and the abundance of epidote which is macroscopically visible indicate extensive alteration. Under the microscope a specimen from this locality, No. 11649, is seen at a glance to be a typical diabase. Although every vestige of the original pyroxene has been

[1] Naumann: Erläuterungen der geogn. Karte der Umgegend von Hainichen im Königr. Sachsen 1871, p. 11. Rud. Credner: Das Grünschiefersystem von Hainichen, Zeitschr. für die gesammten Naturwiss., vol. 47, p. 127, 1876.

[2] Ueber mechanische Gesteinsumwandlungen bei Hainichen in Sachsen, part 2. Zeitschr. Deutsch. geol. Gesell., vol. 31, pp. 374-397. Pl. IX, 1879.

replaced by a finely fibrous green hornblende (uralite), yet the characteristic ophitic or diabase structure is still perfectly preserved. The lath-shaped feldspar crystals are but slightly altered and the spaces between them are as sharply defined as when the rock first solidified.

The northern portion of this little island shows the same diabase in a much more altered form. The rock has a pale greenish color, and, though quite massive in the center, is schistose on either side.

Nos. 11651 and 11652, the former from the massive and the latter from the schistose portion of this rock, offer additional examples of the fact so frequently observed in the Menominee River greenstones, viz, that the feldspar of those rocks which have been subjected to the greatest pressure is more broken, but, as a rule, less altered than that in rocks which have experienced less violent mechanical action. Both of these specimens show positive evidence in their structure that they were once diabases. In both the ophitic arrangement of the constituent minerals is still distinct, but in the more massive rock the chemical alteration has progressed much further than in the other. Here the lath-shaped feldspar crystals are preserved in outline by the various secondary products which supply their place. Fibrous hornblende and leucoxene are abundant and nowhere, in either the thin section or hand-specimen, is there visible any parallelism of arrangement among the components. In the schistose rock, on the other hand, chlorite has largely replaced the hornblende, but the feldspar is almost unaltered. The long, lath-shaped crystals are broken and faulted—the fragments of a single individual often being separated a considerable distance—but in spite of this the substance is as fresh and the twinning-lamellæ are as sharp as in a recently solidified rock. Few better examples could be found of the evident action of pressure upon a solid rock mass. There has been a crushing and a consequent development of schistose structure which the microscope reveals with great distinctness. Along lines where an actual slipping took place, fibrous hornblende, chlorite, and calcite have been quite abundantly developed.

No more typical exposure of the greenstones of the southern Marquette area can be found than that seen in the high hill which rises between Whetstone Brook, the State road, and the railroad. (D on the map, Pl. VII.) The freshest rock obtained from the summit of this hill, No. 11724, is one of the best preserved diabases found anywhere south of the Eureka series. The feldspar is perfectly fresh but is much broken and faulted, as in the specimen (No. 11652) last described. The interstices between the fragments are filled with chlorite. The allotriomorphic pyroxene is now largely replaced by paramorphic hornblende, although cores of the original mineral are not infrequent in the center of the hornblende areas. Apatite, ilmenite, and leucoxene are also present.

Nos. 11646, from the southwest corner of the railroad crossing on Front street, Marquette (see on the map, Pl. VII.), and 11695, collected just

north of the state road (in the center of Sec. 27 T. 48 N., R. 25 W.), are also well defined uralite diabases. In both the structure is still intact and the feldspars are generally well preserved, though the augite is wholly uralitized. One rock of exceptional character (No. 11687) which occurs within the limits of the southern Marquette area, must not be passed over without notice. This outcrops in a small exposure at the end of the road leading westward from Marquette to the Eureka shaft, about two miles from the city (see map, Pl. VII). It is of a light brownish color, and, in spite of an advanced state of chemical alteration, it shows plainly the effects of great pressure. It appears once to have been a gabbro, very similar to that occurring at Sturgeon Falls, on the Menominee River (see p. 67), but now its original components and structure have both disappeared. Interlacing, lenticular areas produce a decided "microflaser" structure, which, in places, even resembles the fluidal appearance of certain vitrophyres. The minerals now present are a very pale chlorite filled with sharp epidote or zoisite needles, saussurite, quartz, calcite, ilmenite, leucoxene grains, and winding bands of a clear, brown, isotropic substance which looks like opal. This rock appears much shattered in the field and it is in immediate contact with the thin, fissile schists in which the Eureka shaft is sunk.

GREENSTONES SOUTH OF THE QUARTZITE.

Some distince south of the Carp River, in the west half of the NW. ¼ Sec. 6, T. 47 N., R. 24 W., below the limestones and quartzite, a few much contorted and altered greenstones appear just on the contact with the granite which incloses the Marquette basin on the south.

No. 11778 may still be recognized as a diabase, though it now contains only saussurite, chlorite, epidote, quartz, and leucoxene.

Nos. 11774 and 11775 are from the same greenstone band, the former massive, the latter schistose. They do not resemble any other rocks in the Marquette area, but they find their analogues in certain remarkable rocks on the south bank of the Carp River, where this is crossed by the road leading northward from Teal Lake (see succeeding section, p. 175). Sharply defined crystals of reddish feldspar are imbedded in a bright green mass of chlorite and serpentine. The feldspars, although not pulled apart as in rocks which have been subjected to a stretching, show evidences of the action of enormous pressure. Remnants of hornblende, from which the serpentine was probably derived; ilmenite, surrounded by leucoxene; and round grains of bright red iron hydroxide are also present in this rock. In the schistose modification, the constituents are pulled out into parallel bands. The feldspars are lath-shaped and smaller, and, without any loss of sharpness in their outline, they are replaced by calcite, which is surrounded by an opaque black rim. Certain bands in this rock are much finer grained and present the feldspar and hornblende in a much less altered condition.

No. 11779, from this same locality, is one of the best specimens any-

where collected to show the effects of rock-stretching. It appears once to have been a granite porphyry, but is now very schistose and is colored green by the secondary chlorite. Its groundmass is a felt-like aggregate of sericite, quartz, and chlorite with a perfectly parallel arrangement of the constituents. The large porphyritic feldspar crystals are much broken and pulled apart, always in the direction of the foliation, as shown in Pl. XIV, fig. 2. Large calcite individuals are surrounded by bright green chlorite, and both of these minerals may represent original biotite or some bisilicate.

ROCKS OF THE NEGAUNEE AREA.

As has already been stated at the beginning of the preceding chapter, two points were selected for the study of the more western portion of the Marquette greenstone belt. One of these was the mining town of Negaunee, situated at the southeast corner of Teal Lake, about twelve miles west of Lake Superior. The town itself is on the iron-bearing Huronian rocks, south of the greenstone belt, whose southern edge skirts the northern shore of Teal Lake. Both east and west of the lake the greenstones are bounded on the south by the narrow ridge of white quartzite, whose termination is Mount Mesnard.

From this quartzite two sections, three miles apart, were run northward to the granite and Huronian rocks, which here divide the greenstones into two separate areas. The more southern of these, which we will designate as the Negaunee area, resembles in its general character the region south of the Eureka series near Marquette; while the region north of the Dead River, which will form the subject of the succeeding section, is much more like the northern Marquette area.

The greenstones occupying the region north of Negaunee do not occur in continuous exposures, but rise out of the plain composed of glacial and later deposits in the form of rounded knobs. Both the longest axis of these knobs and the approximately parallel rows in which they are arranged follow the east and west strike, common to all the rocks of this region. The greenstones are, for the most part, of the much fissured and brecciated, light green and aphanitic variety, described in the last section. They are also very commonly associated with the same coarser and more crystalline eruptives, probably of a much later age, that we encountered south of Marquette.

As will be readily seen from an examination of Dr. Rominger's map the Huronian rocks around and south of Negaunee and Ishpeming are also penetrated by numerous greenstones. These, as a rule, resemble the more crystalline and later intrusions of the greenstone belt proper, and they may have been contemporaneous with them.

APHANITIC GREENSTONES.

The main mass of the greenstone belt near Negaunee is composed of the fine grained or aphanitic rock which has been described in the last

section as characteristic of the region south of Marquette. They belong to Lossen's type of "dichte Diabase" and always show more advanced chemical alteration than the coarser rocks. This is to be explained by their finer grain and also from the fact that they are older and have been subjected to more dynamic action than the others. In the field these rocks are found to be much brecciated and not infrequently quite perfectly foliated. They also exhibit the peculiar spheroidal parting already described, p. 166.

The microscopical appearance of a fair average type of these aphanitic greenstones (No. 11747, from Baldwin's Kilns) is represented in Pl. X, fig. 2, but they show considerable variation in both structure and composition. In none is any trace of pyroxene now to be found, and yet they were probably once typical diabases. Their mineralogical differences are mainly dependent on the relative proportions of hornblende and chlorite. The preponderance of one or another of these minerals may be attributed to a more or less advanced stage of chemical alteration, but certain differences in structure have probably always existed. The grain may vary considerably in its coarseness, while the long acicular feldspar crystals, so abundant in some specimens, are wholly wanting in others.

No. 11736 was collected on the road from Negaunee to Baldwin's Kilns, just beyond the Carp River, from about the center of the SW ¼ of the NE ¼ of Sec. 29, T. 48 N., R. 26 W. It is comparatively coarse grained and little altered. Under the microscope it appears as a confused aggregate of fibrous hornblende, a cloudy, opaque, indeterminable substance and some original feldspar whose crystals are much broken.

No. 11744, obtained from an isolated knob of greenstone, situated in the SW ¼ of the NE ¼ of Sec. 28, T. 48 N., R. 26 W., on the longer road to Baldwin's Kilns, about one mile east of where the last specimen was collected, is much like it in appearance and microscopic character. The only differences are due to the more advanced alteration of the latter rock. Here chlorite is abundant and the feldspar hardly visible.

No. 11745, from the same road as the last, but much nearer the Kilns, shows the spheroidal parting or brecciation in a very perfect manner. The grain is very fine, and the incomplete skeleton-like forms of porphyritic feldspar crystals are numerous. The mass itself is now largely chloritic, but looks as if it might once have been a finely porphyritic rock.

No. 11747, found at the same locality, is the one from which Pl. X, fig. 2, was drawn. It is similar in structure to the last specimen, but its grain is coarser, and fibrous hornblende is still abundant in its groundmass. The porphyritic feldspar crystals are broken, faulted and separated.

No. 11748 is a schistose modification of 11747. This rock has a much finer grain than the other, but no evidence of schistose structure is ap-

parent under the microscope. The chemical alteration has progressed so far that hardly any of the substances remaining have much action on polarized light; nevertheless, faint traces of small acicular feldspar crystals are visible.

One massive greenstone, No. 11740, found just north of Baldwin's Kilns, in the NW ¼ of Sec. 21, T. 48 N., R. 26 W., is striking on account of its being mottled with round white spots from 5^{mm} to 6^{mm} in diameter. The rock is somewhat darker than usual in a rim around these spots, and the whole effect is exactly that of a variolite. Under the microscope the rock itself is found to be composed almost wholly of green fibrous hornblende, together with some opaque grains and saussurite. The round whitish spots are very largely composed of saussurite or a very fine mosaic, in which sharply defined hornblende crystals are imbedded. They do not show the least trace of a radial or sheaf-like arrangement, such as is characteristic of a true variolite. These spots are not unlike those found in the banded greenstones of the Brook section (see p. 157) in their composition and structure, but they are very much more regular and uniform in their shape.

Other specimens of these aphanitic greenstones, as for instance Nos. 11793, 11795, 11796, and 11797, collected along the line of the old logging road, which leads from the eastern end of Teal Lake northward to Johnson's Camp, in the SE ¼ of Sec. 13, T. 48 N., R. 27 W., are quite like those above described from the neighborhood of Baldwin's Kilns.

COARSELY CRYSTALLINE GREENSTONES.

No. 11749, collected in the extreme northeast corner of Sec. 21 T. 48 N., R. 26 W., northeast of Baldwin's Kilns, is an unusually beautiful rock. The structure is coarse grained and rather granular, in spite of the feldspar crystals being idiomorphic. The large individuals of hornblende also, to some extent, have their characteristic crystal form. They are frequently changed to chlorite or to fibrous hornblende, but still oftener, although bleached to a pale green color, they retain their compact texture and show a twinning structure. There are no present indications that this rock ever contained pyroxene, and it is therefore to be designated as a diorite. The hornblende shows, in the process of its alteration, a curious tendency to concentrate the deep green color around the periphery of the crystals; also the fraying out of their edges into hornblende needles similar to those described by Becke and Van Hise as secondary growths, produced by regularly orientated accretions of hornblende substance. All of these features are shown in Plate XII, fig. 1, which represents the microscopic appearance of this rock. The feldspar is filled with epidote or actinolite needles. Large areas of bright green chlorite also occur which contain sometimes sharp epidote crystals, but more commonly fibrous hornblende. Leucoxene after ilmenite is abundant.

No. 11739, from the southeasterly portion of the SW ¼ of the NW ¼ Sec. 21, T. 48 N., R. 26 W., just north of Baldwin's Kilns, is a dioritic rock much like the last, but it is considerably more altered. The hornblende is more fibrous, the feldspar more saussuritized, while the original structure is also beginning to suffer.

No. 11746 was taken from a well marked dike which intersects the spheroidally parted, aphanitic greenstones, near Baldwin's Kilns. Here the diabase or ophitic structure is perfectly developed, and there is no reason to doubt that the pale green, fibrous hornblende, which now fills the allotriomorphic spaces between the lath-shaped feldspar crystals is secondary after augite. The most interesting feature of this rock is its amygdaloidal structure which was observed in no other Marquette greenstone. Several small amygdules are filled with brightly polarizing epidote, while one large circular cavity, measuring four millimeters in diameter, has its sides coated with radiating epidote needles and its center filled with calcite.

No. 11741 is the rock exposed at Baldwin's Kilns. It is much jointed but quite massive. Under the microscope it appears like the specimen last described, except that it is finer grained and devoid of amygdaloidal cavities. The structure of this rock is perfectly preserved. It was once a typical diabase, although now no trace of pyroxene remains.

Another of the more coarsely crystalline dike rocks of the Negaunee greenstone belt was obtained near the granite contact in Sec. 13, T. 48 N., R. 27 W., two and one-half miles north of Teal Lake. This (No. 11791) is a typical uralite diabase, as is shown both by the distinct traces of ophitic structure and by the frequent cores of pale reddish brown augite which still remain in the fibrous hornblende. Ilmenite, partially changed to leucoxene, is also present in forms especially characteristic of diabase. The original structure has been considerably obscured by chemical changes. The feldspar is partly recrystallized to a mosaic, and epidote, chlorite, and quartz have been secondarily developed.

As has been above remarked (p. 171), the greenstones which occur so abundantly in the iron-bearing Huronian rocks both north and south of Negaunee are apparently identical with the coarse grained, younger rocks of the greenstone belt proper. Still they show the effects of having been subjected to enormous pressure which has frequently produced in them a schistose structure; and as this is, in every case, conformable to the general strike of all the rocks of this region, we must conclude that these greenstones were intruded before the folding of the Huronian sediments was completed.[1]

Specimens were collected from the prominent exposures of these greenstones near the town of Negaunee. They are all rather coarse uralite diabases of the type last described from the greenstone belt.

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[1] See sections by Brooks, Atlas to Geol. Survey Michigan, Pls. III and V.

No. 11754, collected from the SW ¼ of the SW ¼ Sec. 6, T. 47 N., R. 26 W., near the mouth of the Jackson mine, has a well preserved diabase structure. Its pyroxene is wholly changed to pale secondary hornblende; its feldspar is filled with epidote, while chlorite and leucoxene are common.

No. 11755, from a high hill somewhat farther east, is essentially the same rock. It contains epidote and chlorite even more abundantly.

No. 11756 was collected from a small greenstone knob just east of the hotel (Breitung House) in Negaunee. This rock has been quarried and may be plainly seen to have been rendered partially schistose by pressure. Under the microscope it is like the preceding rocks except that alteration has here progressed further—so much so as to have obscured, though it has not obliterated, the original diabase structure. Chlorite, epidote, and calcite are among the prominent constituents.

Nos. 11758 and 11759 are from the greenstone bluffs which skirt the southern shore of Teal Lake near its eastern end. The former is the most massive, the latter a schistose variety of this exposure. The massive rock is a uralite diabase of the ordinary type, retaining its original structure and also occasional cores of red augite in the masses of secondary hornblende. Besides the usual chlorite, epidote, and leucoxene, there is considerable quartz present in this rock. The second specimen, taken from the schistose band on the south side of this greenstone ridge, shows evidence of intense mechanical and chemical action. The original structure has almost wholly disappeared, while its component minerals are calcite and chlorite, together with a little quartz and leucoxene. Rarely these secondary products have preserved the outline of lath-shaped feldspars, which show that they have been much broken and pulled apart by the stretching action to which the rock has been subjected.

THE STRETCHED FRAGMENTAL ROCKS ON THE CARP RIVER.

An enigmatical group of rocks was met with near the center of the Negaunee greenstone belt, where the old road leading to Johnson's logging camp crosses the Carp River. This locality is in the NE ¼ Sec. 25, T. 48 N., R. 27 W. The first rock south of the river is exposed in a low wall which rises just west of the trail. (No. 11798.) This is apparently a dark colored, schistose greenstone, standing nearly vertical and filled with red granite fragments of all shapes and sizes, though generally with well rounded outlines. The dark green matrix also contains much of the red material in a finely divided form, often resembling sharp crystals. The rock itself is much brecciated and cut by cross-gashes, as if it had been subjected to a stretching tension.

Under the microscope the dark green portion of this rock is found to consist entirely of chlorite, the scales of which are arranged parallel to each other and to the cleavage planes of the mass. Its color, when free from inclusions, is a clear, bright green, but it frequently contains con-

siderable black or brownish opaque material, which is arranged in long, sinuous lines following the foliation. The reddish inclusions are almost altogether orthoclase, colored by a fine, unevenly distributed, globulitic dust. A striated feldspar may also be occasionally observed. The orthoclase is partly in sharply defined crystals, but more commonly in irregular and angular fragments. These range through all sizes down to the most microscopic dimensions. The smallest bits are locally scattered so thickly through the chlorite as to give the rock a decidedly clastic appearance.

The chlorite matrix is of that peculiar character which we have already had occasion to notice as characteristic of stretched greenstone, particularly in the Menominee Valley (see pp. 82, 83, and Pl. XI, fig. 2). This chlorite must have crystallized after the orthoclase fragments had come into their present relative positions, as may be seen from the relations of its scales to the feldspar, and also by the bending around these fragments of the sinuous bands of opaque matter which the chlorite sometimes contains. We may go even further and assert that the chlorite could not have been formed prior to the stretching action. Proof of this is to be found in the fact that some of the orthoclase inclusions may be plainly seen to have been broken during this process and their fragments to have been separated but a short distance and always in the direction of the foliation; *and yet the same chlorite which forms the whole matrix fills these late fissures.*

It is impossible to state anything positive with reference to the origin of this chlorite; and still its universal presence in the stretched greenstones would indicate that this particular form of dynamic action upon a mass of the proper chemical composition is, in some way, necessary, or at least very favorable to its production.

No. 11799, from the same locality, is essentially like the last specimen, except that the included feldspar is lighter colored and perhaps more altered to kaolin or muscovite. The matrix is not so purely chloritic, but contains much finely divided feldspar. The stretching action is here even more apparent, a single feldspar crystal being pulled out to over double its original length and its fissures being filled with the same green chlorite.

If we trace this ridge farther south it develops into a finer grained and more schistose greenstone, which is free from the larger granitic inclusions but is mottled with small white spots (No. 11800). These are found upon closer examination to be feldspar crystals. Under the microscope this rock is quite like those above described, but it shows much more distinctly the effects of dynamic action. The grain is very uneven. In some places the feldspar crystals are thickly crowded and are cemented by the usual chlorite in which epidote is abundant; in other places the matrix is a very fine grained aggregate of chlorite, sericite, quartz, and feldspar, containing considerable opaque substance and possessing a micro-flaser structure produced by the winding of its

parallel bands about the occasional feldspar inclusions. These latter are much pulled out in the direction of the foliation and have their interstices filled, sometimes by the chlorite, but oftener still by calcite.

No. 11801 is a more weathered specimen of this same rock, which shows with great distinctness the spheroidal parting described above (see p. 166). The stretching action is here displayed by the pulling out of the spheroids into a system of interlocking lenses, as represented in Fig. 27. Under the microscope this rock shows the effect of the me-

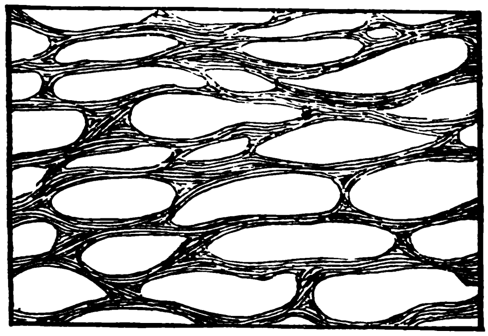

FIG. 27—Spheroidal parting of aphanitic greenstone produced by brecciations; drawn out into lenses by pressure. Scale same as in Fig. 26.

chanical action in the extremest degree. The matrix is very schistose and consists of a gray, indeterminable, almost isotropic mass in which minute flakes of sericite are distinguishable. The feldspar crystals are so altered that they seem to grade imperceptibly into the matrix, leaving their original shapes but indistinctly outlined. The dark green chlorite occurs only in rare patches.

No. 11802 is from the interstitial mass between these lenses. It is a finely fibrous, felt-like, sericitic mass, in which the scales are so strictly parallel that the entire slide extinguishes the light between crossed Nicol prisms almost like a homogeneous crystal. There are besides present only small patches of a light brown, isotropic substance, some little quartz in isolated areas, and long stringers of leucoxene, out of which minute but sharp, highly refractive octahedrons have been developed (anatase ? cf. No. 11130, p. 131).

No. 11803, also from this interstitial material, contains white feldspar crystals like the more massive cores. A microscopic examination shows that this specimen is in all respects identical with the rock which it surrounds. The schistose structure is due to a crushing accompanied by a tension in one direction. The effect of this is so striking on the included feldspar crystals that it has been selected for illustration. (Pl. XIV, fig. 2.)

After a careful study of this suite of rocks, which is distributed over a considerable area, it is impossible to escape the conviction that they are of a fragmental character. Neither their structure nor their

mineral composition resembles that of any known eruptive rock while the sudden variations in grain, the irregular and angular shape of the feldspar inclusions, and, above all, the extreme differences in the size of even such of these inclusions as lie side by side can be reconciled only with a clastic origin. Still these rocks do not bear the stamp of true sediments, and the most probable hypothesis of their nature which the writer can offer is that they are deposits of volcanic ejectamenta which have subsequently been rendered schistose by dynamic agencies. The irregular and angular fragments of red granite must be regarded as material broken from off the underlying rock masses and hurled out by the violent explosive force, along with much finer rapilli, sand, and ashes. These rocks seem to agree very closely with the agglomerates described by Mr. A. C. Lawson, of the Canadian Geological Survey, as attaining an extensive development in the Lake of the Woods region. These are filled with angular fragments and have also been subjected to great pressure. Mr. Lawson's opinion regarding the origin of these agglomerates is the same as that above advanced.[1]

The presence, as here, of the spheroidal or lenticular parting in rock of fragmental origin is sufficient to show that it must be a mechanical and not a molecular phenomenon.

ACID ROCKS.

There were no acid intrusives encountered within the Negaunee greenstone area proper, nor do the granites which skirt the northern edge of this belt present any points worthy of especial note.

No. 11790 is the granite in immediate contact with the greenstones at the end of the section which was run northward from Teal Lake. It was found at the Johnson logging camp in Sec. 13, T. 48 N., R. 27 W. This is a typical granitite in which quartz is not very abundant. The biotite is quite altered and bleached. The feldspar is particularly distinguished by its beautiful zonal structure, which the incipient kaolinization has brought out all the more distinctly. This feldspar shows the effects of pressure, and in one instance this can be plainly seen to have resulted in the production of a microcline structure. One small, sharp crystal supposed to be orthite was observed in this rock. Apatite and zircon also occur, and occasionally a few rutile needles are secondarily developed in the altered mica.

No. 11738 is from the granite in contact with the greenstone just north of Baldwin's Kilns. This rock is completely crushed, the constituents being in some cases so pulverized as to give the specimen, when seen under the microscope, almost the appearance of a fragmental deposit. The mica is here much altered, and among secondary products has given rise to an abundance of most delicate rutile needles, which often form the characteristic twins.

[1] Geol. and Nat. Hist. Survey of Canada. Ann. Rept. for 1885, p. 49, CC.

Here may conveniently be recorded some observations made on the quartzite of the ridge which borders the greenstones on the south in the neighborhood of Negaunee. This quartzite mass is composed on its northern or lower side of compact, even grained, thinly laminated rocks, varying in color from black to the lighter shades of green, yellow, and drab. At one point, near the northeast corner of Teal Lake, these have been quite extensively quarried as novaculites, although they are of a different character from the novaculites occurring near Marquette. These rocks have the usual east and west strike and dip steeply to the south. These so-called novaculites are again underlaid by conformable beds of a coarse, white quartzite conglomerate, which in its turn is in immediate contact with the greenstones. The best locality for seeing these contacts is on the wood road leading northeastward from the slaughter-house on Teal Lake. (NW ¼ Sec. 31, T. 48 N., R. 26 W.)

No 11785 is a nearly black specimen of the novaculite. Under the microscope the fragmental character of this rock is at once apparent. It is composed of irregular quartz and altered feldspar grains in nearly equal proportions. In the finer cement biotite has abundantly crystalized. An occasional zircon crystal would seem to indicate that the rock is the stratified debris of an old granite. The present foliation of these novaculites is to be regarded as a slaty cleavage due to pressure, rather than an original stratification.

The conglomerate between the novaculite and greenstone, and forming the base of the Huronian quartzite, is composed of large grains and pebbles of granitic quartz, imbedded in a fine, silky matrix of sericite. (Nos. 11787 and 11788.)

ROCKS OF THE NORTHERN AREA.

The second point selected for the examination of the western portion of the Marquette greenstone belt is near the center of Sec. 9, T. 48 N., R. 26 W. Here a camp was established and from it were studied the greenstones represented upon Dr. Rominger's map as occurring north of the Dead River. The rocks within this area present a much more varied character than those of any of the other areas examined. Indeed, although a considerable collection of specimens was made, it is not for a moment supposed that all the types of massive rocks which occur in this region were obtained. Enough, however, will be noticed to indicate the general character of the area and at the same time to illustrate the extreme variety offered by different, and often nearly contiguous, outcrops.

In its chief features, this area more closely resembles the northern portion of the belt near Marquette, just as the southern branch near Negaunee, as stated in the preceding section, is more like the southern Marquette area. Still, the more recent eruptive rocks which penetrate the banded green schists far exceed, both in amount and variety, those to be found nearer Marquette.

UNALTERED BASIC INTRUSIVES.

At the falls of the Dead River, in the southwest corner of Section 9, the "arenaceous slate group" of Rominger is well exposed. This consists here of thinly bedded slates which strike N. 75° W. and stand nearly vertical, with perhaps an inclination to the south. The upper part of the fall is a steep incline over the slates, but the lower portion is a clear fall of from twenty-five to thirty feet, occasioned by several trap dikes which run nearly east and west. These are coarse grained, fresh, and sometimes porphyritic.

No. 11814, from one of these dikes, is found, under the microscope, to be a very fresh and typical olivine diabase, quite like that of the great dike on Lighthouse Point, Marquette. The structure is typically ophitic. The porphyritic appearance is occasioned, not by single individuals of feldspar, but by concretionary aggregates of this mineral. The olivine, which frequently presents crystal outlines of great sharpness, is sometimes completely, sometimes only slightly serpentinized.

No. 11826 was collected from an outcrop beside the road at the southwest corner of Sec. 10, T. 48 N., R. 26 W. It has every appearance of being in place, but the character of the rock, unknown elsewhere in this region, renders it much more probable that it is a portion of a huge glacial erratic which is nearly buried in the drift. Still, the petrographical interest of this rock makes it worthy of a description. A close examination shows it to be an olivine gabbro, perfectly fresh and peculiar on account of the abundance and beauty of its olivine. This constituent makes up a large percentage of the entire mass. It is present in extremely sharp and well formed crystals from 0.1 to 1^{mm} in diameter. These show the usual hexagonal cross-sections, due to the presence of faces of the prismatic zone and domes.[1] No signs of even incipient alteration are visible in this olivine. The augite and triclinic feldspar are both allotriomorphic, and form much larger individuals than the idiomorphic olivine which they inclose. Magnetite is abundant in sharp octahedral crystals, showing quadratic sections; while other irregular areas of an opaque black iron mineral may be ilmenite. These latter are often partially bordered by a dark brown mica. No other rock exactly like this is known to me, but in its general character it is allied to the olivine gabbros which play such an important role on the north shore of Lake Superior.[2]

ALTERED COARSE GRAINED ROCKS.

The coarser grained intrusive rocks, which penetrate the prevailing green schists of the northern area, have, as a rule, undergone a considerable amount of chemical alteration. This has more or less completely replaced the original minerals by secondary products; while, in some

[1] These crystals show indications of twinning, as described by Kalkowsky (Zeitschr. Kryst. u. Mineral, vol. 10, p. 17) but these are not as distinct as the sharpness of the crystals would lead us to expect.
[2] Cf. Irving; Mon. U. S. Geol. Survey, vol. 5.

cases, it has also obliterated the original structure. Among these younger eruptive greenstones the same two types can be distinguished as in the Marquette area, viz, diorite and diabase.

Diorite—Nos. 11828 and 11829 are from an exposure thirty paces in width, on the line between Secs. 5 and 8, T. 48 N., R. 26 W. This rock is sometimes parted into parallel plates so as almost to resemble a slate. In the hand-specimen it is seen to be composed of rather large, well-formed hornblende crystals, which are often hollow at the center, and a reddish feldspar. The microscope shows that the two specimens are identical. The hornblende is idiomorphic, though without terminal planes; the feldspar, on the other hand, is wholly allotriomorphic. This latter mineral is almost free from twining striations, so that the rock were perhaps more properly termed a syenite. The hornblende preserves much of its compact structure and brownish color. It is frequently changed at the center to a mass of fibrous needles, or even to chlorite, while the exterior remains compact and unaltered. Apatite is very abundant; sphene and magnetite are not uncommon.

No. 11817, from a wide dike at the northwest corner-post of Section 9, of the same township, is of the same type as the last specimens, but more altered. Macroscopically tufts of hornblende crystals may be seen imbedded in a white feldspar substance. Under the microscope this feldspar appears to be mostly altered to a brownish saussurite, in spite of which, however, traces of a stout lath-shape are discernible. The hornblende is much altered to a fibrous form. It frequently has the emerald green color of actinolite, especially around the outer edge, where it is always darker and more compact than at the center. Ilmenite, accompanied by leucoxene, is abundant in the rock, though absent in the two last mentioned specimens. It will be noticed that this rock approaches much more nearly than the others to the diabase type, and yet there is no reason to believe that the hornblende is paramorphic after pyroxene. Although it is not compact, it still retains its twinning structure as one of its most common features.

A still more striking example of idiomorphic, lath-shaped feldspar in a diorite (a structure which Rosenbusch mentions as not at all uncommon in rocks of this class[1]), is to be found in No. 11831. This was obtained on the line between sections 5 and 8, just east of Nos. 11828, 11829, above described. It is entered in the field-notes as a coarse reddish diorite or syenite, having long, green hornblende crystals imbedded in a red feldspar. On account of its unstriated feldspar, this rock may perhaps be even more properly designated as an amphibole granite, although its structure is in many respects peculiar. (See Pl. XVI, fig. 2.) The feldspar is present in two distinct generations. The earliest of these yielded stoutly lath-shaped crystals, which are wholly idiomorphic. These are mostly unstriated, but have a zonal structure. They are internally changed to a grayish mass, which a

[1] Mikros. Physiog., 2d ed., vol. 2, p. 121.

high magnifying power shows to be muscovite or kaolin, while their periphery is composed of clear and fresh feldspar substance. Between these feldspar crystals is a granular aggregate of quartz and a younger feldspar. This latter mineral is also unstriated (though sometimes possessed of the gridiron microcline structure) and much fresher than the older feldspar. With the quartz it frequently forms beautiful micropegmatitic growths.

Hornblende was most probably the original bisilicate constituent of this rock, but it has undergone an unusual alteration, i. e., the alteration to mica. This mineral can be seen under the microscope in brown areas of irregular shape, which have evidently been produced at the expense of the hornblende.[1] They are unevenly colored, being a darker brown in some places than in others. In some cases the new mica crystallizes in sharply defined hexagonal plates. Certain of these, which on optical examination prove to be basal sections, show cleavage lines parallel to the prismatic faces. These are the so-called pressure figures ("Drucklinien" of the German mineralogists), which are rarely visible in microscopical sections and are strongly indicative of pressure.

This secondary mica to a considerable extent has turned green by a reduction of its iron to a ferrous state. More rarely the alteration has progressed still further, resulting in complete bleaching, or even the production of chlorite. Apatite is very abundant in this rock; sphene is also common, but its crystals always surround ilmenite grains in such a manner as to suggest that the titanite has resulted from its alteration (see Pl. XVI, fig. 2). Chlorite also frequently surrounds the opaque iron mineral.

Of all the remarkable features which this rock presents, perhaps none is more striking than its hypidiomorphic structure and the presence of the feldspar in two distinct generations without the production thereby of a porphyritic structure. This is all the more noteworthy in a rock which from its mineralogical composition is to be strictly classed among the granites.

No. 11832, which occurs with the specimen last described, appears to the unaided eye as a compact, fine grained mass through which large glistening hornblende crystals are unevenly distributed. Under the microscope the groundmass of this rock is seen to be composed of lath-shaped feldspar crystals, which are altered sometimes to epidote, sometimes to sericite; allotriomorphic hornblende, frequently changed to chlorite; a little quartz and magnetite in grains and crystals. The sharp quadratic and hexagonal sections are sufficient to identify this species; but we must assume that it is a titaniferous magnetite on account of the very narrow leucoxene border which

[1] Rosenbusch mentions only parallel growths of hornblende and biotite. The present instance can hardly be so interpreted, while there is nothing surprising in an alteration which has been so frequently observed. (Cf. J. Roth: Allgemeine und chemische Geologie, vol. 1, p. 333, 1879.)

frequently surrounds it. The porphyritic hornblende of this rock is sometimes regular, sometimes irregular in outline. It is a later crystallization than the groundmass, because it is always filled with the lath-shaped feldspars. This produces the structure which I have recently termed "poicilitic,"[1] and which is characteristic of younger porphyritic crystals, especially hornblende and pyroxene.

No. 11834, from a ledge 640 steps north and 20 steps west of the southwest corner of Sec. 4, T. 48 N., R. 26 W., is composed of stout, lath-shaped feldspar crystals and large individuals of fibrous hornblende. The former mineral suggests by its form that the rock was once a diabase; the hornblende, however, is not allotriomorphic, but is present in long, columnar crystals, which are generally twinned. One of these crystals is bent in the most unaccountable manner. It forms three-quarters of a circle (see Fig. 28), but no satisfactory explanation can be offered for this unusual shape.

On the whole, this rock is considerably altered. Epidote and hornblende needles are developed in its feldspar, while secondary quartz is quite abundant. In spite of the fibrous character of its hornblende, the structure of this rock is much more suggestive of a diorite than of a diabase.


FIG. 28.—Bent hornblende crystal. Greenstone No. 11834. Magnified 30 diameters.

Diabase.—Among the altered intrusive rocks, those which represent the diabase type are all uralite diabases. In none was any trace of the original augite observed.

In No. 11827, from 485 steps west of the southeast corner of Section 5, the structure is best preserved. Here the fibrous and in part bright emerald green hornblende retains exactly the allotriomorphic form of the diabase augite. The feldspar is largely altered to a brown, opaque saussurite, and leucoxene has replaced the ilmenite.

No. 11837, from 815 steps north of the southwest corner of Section 4; No. 11848, from 500 steps west of the southeast corner of Sec. 10, T. 48 N., R. 26 W., are both much more altered than the specimen last mentioned. The ophitic structure is best preserved in the latter, although epidote is abundantly developed, while it is altogether wanting in the former.

Other of these uralite diabases are finer grained.

No. 11825, from a somewhat schistose greenstone ridge, exposed near the center of the southwest quarter of Section 10, admirably exhibits the effects of crushing. The lath-shaped plagioclase crystals are still

[1] Am. Jour. Sci., 3d series, vol. 31, 1886, p. 30.

wonderfully fresh, but are broken, faulted, and pulled apart, while their interstices are filled with the secondary chlorite usual in stretched rocks. There is a delicate granophyre or micropegmatite structure in this specimen—undoubtedly an original feature, as in No. 11675 (see p. 140). The pyroxene is wholly changed to a pale green, fibrous hornblende, which, to a considerable degree, produces the foliation. Large areas of brown leucoxene, of the variety most characteristic of altered diabase, are also drawn out in the direction of the schistose structure. In one instance this has altered to a network of dark rutile needles imbedded in a yellowish micaceous mineral, as described in No. 11070 (see p. 99, and Plate XIII, fig. 2).

No. 11830, from 700 hundred steps west of the southeast corner of section 5, is a very typical uralite diabase. The structure is still well preserved by the feldspars, in spite of needles of the fibrous hornblende having freely wandered into them. Traces of augite cores remain in this rock.

No. 11835 is a schistose rock from 640 steps north and 20 west of the southeast corner of Section 5. It has been much altered, and now consists mainly of a fine aggregate of fibrous hornblende, feldspar, quartz and calcite. In this lie large porphyritic crystals of hornblende which are wholly altered, especially in their interior.

BANDED GREENSTONES.

Striped and banded greenstone schists, like those of Lighthouse Point, Marquette, are very abundant in the northern area.

No. 11856, from an exposure near the northeast corner of Section 9, is macroscopically identical with the Marquette rocks. Under the microscope it would be designated as a hornblende schist. It consists of minute crystalloids of compact green hornblende, together with feldspar which is mostly changed to sericite. Zoisite in crystalloids, like those represented in Fig. 2, p. 27, and about the size of the hornblende, is also present. The structure of this rock is schistose, caused by the parallel arrangement of all the constituents.

Other banded greenstones from this region, like No. 11818, from near the southeast corner of Section 5; 11821, 850 steps north of the southwest corner of Section 4; 11839, 170 steps south of west quarter post of section 4, and 11841, 180 steps north of the same quarter post, are essentially like the specimen just described—mostly a mass of confused hornblende fibers with more or less feldspathic substance, quartz, and chlorite. The relative proportions of these components condition their different colors and cause the parallel striping.

These rocks are so similar to those occurring immediately north of Marquette, that we must apply to them the conclusion already expressed (p. 158) in regard to the origin of these green schists, and regard them as basic tuff deposits, which were contemporaneous with surface flows of diabase and subsequently profoundly metamorphosed.

GREEN SCHISTS AND AGGLOMERATES OF DEER LAKE.

After the work on this paper was practically completed, my attention was called by Prof. Irving to a group of greenstone schists and conglomeratic rocks which lie in the western extension of the southern branch of the Marquette greenstone-schist belt. I was unable to study and collect these rocks in the field, but Prof. Irving furnished me with notes regarding their distribution and mode of occurrence, together with a suite of hand-specimens and thin sections for laboratory study. I incorporate the results of such a study in this place the more willingly because the occurrence of these rocks does not in the least differ from that of others closely allied to them, which I carefully examined in the neighborhood of Negaunee. The distinct evidence, moreover, which these rocks afford as to their mode of origin is of great valuė in confirming the conclusions already reached in regard to certain other analogous, though less distinctly characterized, occurrences.

These peculiar rocks are best exposed on the south side of Deer Lake in Secs. 33 and 34, T. 48 N., R. 27 W., Michigan, but they may also be advantageously seen farther to the northwest, in Secs. 20, 21, 29, and 30 of the same township.

The following field-notes were furnished me by Prof. Irving:

On the road going northward from Ishpeming to Deer Lake furnace a belt of quartzite dipping southward is crossed in the middle of Section 34. Immediately north of this quartzite follows a porphyritic greenstone of tolerably fresh aspect. This is exposed on the south side of the two knobs, which, on Dr. Rominger's map, lie to the southward of Deer Lake, to the east of the Carp River, and to the north of the road. To the northward of this greenstone succeed first some greenish schistose rocks without apparent agglomeratic character. These are represented by No. 12057. These schists soon grade, however, both across the strike toward the north and in the course of the strike toward the west, into a most strikingly conglomeratic rock, which appears to make up about all the hills in the northern half of Section 33, between the quartzite and the road leading to the Ropes mine.

Specimen No. 12058 is an obscurely conglomeratic rock, collected about 150 steps north of No. 12057. The conglomeratic character is best seen on a weathered surface. A particularly fine exposure may be seen just west of Deer Lake furnace (No. 12031).

Specimens No. 12029 are pebbles from a bold knob somewhat farther to the west. From the same point came Nos. 12023 and 12024, representing the conglomerate itself; and Nos. 12025 and 12026, from two dikes two and one-half and ten feet wide respectively. The smaller of these dikes cuts the conglomerate in a direction transverse to its foliation, while the larger runs parallel to this structure.

Throughout the conglomerate there is a tendency to schistose structure, which, however, is never very pronounced, and which varies considerably in its degree of development. It seems to be rather the result of the intersection of close joints cutting each other at a small angle than a true parallelism of structure. This foliation stands about vertical and trends in an eastern and western direction.

The pebbles vary in size from such as are two feet in diameter down to minute fragments. Pieces less than six inches in length are most abundant. Occasionally they appear well rounded, and this seems to be more particularly the case with the larger sized pieces; but more commonly they are sub-angular and flattened out in a direction parallel to the schistose structure. On an exposed surface these pebbles

stand out by virtue of their whiter weathering. On a fresh fracture they are not nearly so apparent, but seem to differ from the rest of the rock by their finer grain and by their pinkish or greenish color; the body of the rock having usually a dark greenish gray tint.

No other kinds of pebbles were seen than those shown in the samples, which represent perhaps two phases: (1) A pinkish weathering felsitic (?) kind, and (2) a grayish weathering greenish and more schistose kind. But this distinction, written on the ground, seems hardly to be borne out by the specimens brought away. Certainly those of the first named kind are more abundant.

Occasional schistose bands a few feet in width and quite free from pebbles may be seen in the conglomerate, trending east and west. These, therefore, stand at a considerable angle with the schistose structure. They are the only signs of a true bedding in the rock, and if they do actually indicate a bedding are of very great importance, both as showing a discordance between the bedding and schistosity and also a nonconformity between these and the true bedded rocks lying just to the south. Indeed, neither these doubtful bedding bands nor the schistose structure perceptible in this conglomerate is concordant with the dip of the quartzite, which is toward the south at a moderate angle.

North of the road leading to the Ropes mine the only rock noticed, for a short distance, is represented by No. 12032, which does not show any conglomeratic structure, but which on the ground appeared very much like the pebbles in the conglomerate further south.

Still farther north, in the same township (T. 48 N., R. 27 W.), as, for instance, in the middle and eastern part of Section 21, and again in the southwest quarter of Section 20, and in the northwest quarter of Section 29, to the north of Dr. Rominger's serpentine area (peridotite area of Plate I, herewith) are other very similar rocks. Specimens 12036, 12037, and 12039 are from the SW ¼ of SW ¼ Sec. 20, while No. 12043 is from the NW ¼ Sec. 29. Among the exposures from which this last specimen was taken are some which seem to show the conglomeratic character of the Deer Lake rocks. It is not positive, however, that the obscure markings which they show are really those of pebbles.

Both the macroscopical and the microscopical examination of these specimens show that they have been subjected to an intense strain or stretching, which has resulted in the elongation of the component pebbles, and in the modification and partial recrystallization of the matrix, after the manner shown in Pl. XI, fig. 2, and in Pl. XIV, fig. 2. Nevertheless, the metamorphism attendant upon this dynamic action fortunately has not been sufficient entirely to disguise the tuff nature of the rock. In most cases this is still very apparent, and this occurrence is therefore of great importance in confirming the conclusions reached with regard to analogous, but more metamorphosed rocks, in the Marquette and Negaunee areas.

We must regard these tuffs or agglomerates as originally composed of the fine fragmental material of diabase. This consisted mainly of triclinic feldspar and pyroxene, mingled with more or less amorphous base, and stratified either by gravity or by the agency of water. Included in such a matrix were numerous true bombs of solid diabase and ejected fragments of other rocks, mostly of a more acid character.

As is well known, material of this kind is of all the most liable to undergo chemical alteration. This has been conclusively shown by the observations of Captain Dutton, quoted above (p. 159). In consideration

of the great antiquity of the deposits here under discussion, therefore it need excite no wonder that little of the original material now remains. The rocks are largely composed of such secondary products as chlorite, sericite, epidote, quartz, and calcite. All traces of original pyroxene, or of possible olivine and glass, have wholly disappeared. The feldspar has, however, better retained its individuality. In some instances its substance is still quite fresh; and in others, where the substance is changed, the form is still easily recognizable. The same class of alterations has gone on in the solid portions of the agglomerates as in the finely fragmental matrix. The more basic fragments produce chloritic, the more acid sericitic, areas. Their original boundaries are, however, for the most part, very distinct, often more so in the field, or in the hand-specimen, than under the microscope. Where the dynamic action has been most intense a schistose structure has been developed in the fragments, which is quite continuous with that of the finer grained matrix. This is accompanied by a distortion or elongation of the included fragments, caused by crushing and recementing, whereby the sharpness of their outline is destroyed, and an apparent transition to the matrix is produced.

Specimen No. 12057, described in the notes as "a greenish schistose rock without apparent agglomeratic character," appears under the microscope at first glance as a confused aggregate of chlorite, calcite, and quartz, through which occasional large grains of yellowish green epidote are scattered. Characteristic forms of ilmenite, with leucoxene, some sericite, and delicate little rutile needles are also present. A more careful study of this section reveals the indistinct outlines of lath-shaped feldspars, which once formed the interlacing network of a granular diabase. These are so disguised by the new products developed in them—chlorite, sericite, and epidote—that it is only by an attentive examination with a low magnifying power that they can be recognized. They are, however, undoubtedly present, and the rock must therefore be regarded, not as a tuff, but as an extremely metamorphosed form of a massive flow, in which the profound chemical changes and the development of a schistose structure progressed together.

Specimen No. 12058, "an obscurely conglomeratic rock collected about 150 steps north of the locality of No. 12057," bears in the hand-specimen a close resemblance to the one last described, but under the microscope its different character is at once apparent. The feldspar substance is here less altered, and the rock is mostly composed of minute crystals or fragments of crystals connected by that peculiar aggregate of chlorite scales common in stretched basic rocks, where the direction of the scales follows the schistose structure. (See Pl. XI, fig. 2.) Occasional larger fragments of feldspar crystals are scattered through this finer mass, but these are always broken and irregular in shape. The chloritic substance has doubtless originated from the pyroxene or glass, while a vast number of the most delicate little rutile

needles, arranged in long, sinuous bands, appears to represent the original ilmenite. Calcite areas also occur. A narrow white vein which traverses this hand-specimen possesses an interesting microscopic structure. The little fissure was first coated with chalcedonic quartz, and then with a layer of quartz crystals which projected their terminations into the opening. These possess a perfect zonal structure, due to the arrangement in successive layers of fluid inclusions. The remainder of the space was subsequently filled with carbonate.

Specimen No. 12031, from a point a short distance west of where the last mentioned pieces were collected, and Nos. 12023, 12024, 12029, and 12030, from another point still farther west, represent the agglomerate in its most typical development, and leave no doubt as to its true nature and origin. As in the specimens last mentioned, the matrix of the rock is of a grayish green color and the grain is mostly aphanitic, although frequent minute angular fragments may be detected by the aid of a pocket lens. There is always a more or less pronounced foliation developed in this matrix. The pebbles, which impart to the rock its agglomeratic structure, show most distinctly on a weathered surface. Here they present a white or pinkish gray color, which contrasts most sharply with the pale green of the inclosing matrix. On a fresh fracture the inclusions have a greenish gray color, but their compact, fine grain, like that of halleflinta, serves to identify them where the color fails. These massive felsitic fragments are of varying size and angular or subangular in shape (rarely well rounded). They are distributed through the matrix indiscriminately, the longest axes being by no means parallel, as we might expect in a sediment. The foliation of the rock appears to have been produced by a great tension, which has stretched the matrix and sometimes elongated the pebbles, sometimes broken them, and sometimes forcibly torn the solidified matrix away from them. The latter case is represented in Fig. 29, which represents

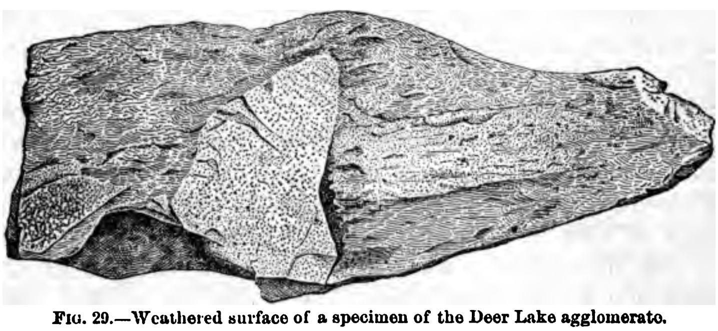

FIG. 29.—Weathered surface of a specimen of the Deer Lake agglomerate. Natural size. No. 12023.

the appearance of a weathered surface on specimen No. 12023. It can here be plainly seen that the longest axes of the pebbles stand almost at right angles and that the matrix has been forcibly separated by the stretching action, on each side of the central pebble.

The microscopical study of these specimens adds much to our knowledge of the true structure of these agglomeratic rocks.

The matrix is found to be composed of very angular to subangular fragments, extending down to the minutest size. These generally still retain their form, although their original substance has undergone change to chlorite, epidote, and calcite. Small feldspar crystals or broken fragments of larger ones are scattered about, the substance of which has been altered in varying degree. In the chlorite especially, very sharp rutile needles abound. These seem to represent the titanium of an original ilmenite.

Unmistakable evidence of clastic structure is everywhere encountered; but this is not the clastic structure of a sediment. The angular shape, different substance, and enormous variation in the size of fragments lying side by side, all clearly indicate an agglomeration of volcanic detritus—and one, indeed, in which many of the original features are admirably preserved.

Among the smallest of the included fragments, those resembling a massive diabase in structure are not uncommon; but to judge from the statement in the field notes quoted above, as well as from the hand-specimens submitted to me for study, the larger "pebbles" or fragments are mostly composed of the lighter and felsitic rock. This is unfortunately too much altered to allow of a wholly satisfactory diagnosis. It may be best seen in section No. 12023, where it resembles a porphyrite. The groundmass still retains its ophitic structure, and is filled with well formed porphyritic crystals of plagioclase. No original quartz nor orthoclase could be detected; one or two chloritic areas, which most probably represent former augite or hornblende crystals, were, however, observed.

Specimen No. 12025 represents a narrow, transverse dike of massive greenstone, and No. 12026 a broader one of the same material, parallel to the schistose foliation. Under the microscope both are typical, though highly altered diabases. The former is aphanitic and has only a very indistinct foliation in the hand-specimen. Under the microscope the original structure is nearly obliterated; still, traces of it remain. Chlorite, calcite, quartz, and iron oxide are almost the only mineral components.

The second, coarse grained diabase, is entirely massive in the hand-specimen. It has an even green color, but cleavage surfaces of feldspar are frequent. Pyrite is also common in it. Under the microscope the typical diabase structure is perfectly preserved. The texture is quite coarse, and the feldspars mostly retain their twinning structure. The rock has been stretched, and these feldspars are much broken and have their fragments separated. The pyroxene is wholly altered to chlorite, epidote, and calcite, and the ilmenite is accompanied by leucoxene.

The rock occurring north of the road leading to the Ropes mine and

directly west of Deer Lake, is devoid of conglomeratic structure. (No. 12032.) In the field it was noted to have a resemblance to the substance of the larger "pebbles," and this resemblance, to a certain extent, is borne out by the microscopical examination. The rock appears to be massive, and not a tuff; but it has been subjected to intense crushing and stretching action. It is full of porphyritic crystals, which are mostly altered to muscovite. The groundmass is principally composed of small rectangular feldspar crystals. All, however, are much broken and separated, and the interstices are filled with green chlorite scales. The main difference between this rock and that forming the compact felsitic pebbles in the agglomerate lies in the apparent orthoclastic nature of the porphyritic feldspar crystals, and in the chlorite which has been so abundantly developed in the groundmass.

The specimens from the more northerly areas, numbered 12036, 12037, 12039, and 12043, belong to the same category as those just described. No. 12036 is a confused aggregate of feldspar fragments of various sizes, together with some quartz and chlorite. Nos. 12039 and 12043 are almost too much altered to allow of any study. The former is a mass of nearly opaque decomposition products, and the latter is an almost continuous mat of sericite scales. No. 12037 alone appears like a massive rock—most probably a fragment included in the tuff. It is a hornblende granite, with but little quartz, composed principally of idiomorphic feldspar. The minute green hornblende needles fill the interstices between these square or rectangular crystals.

We may, therefore, consider the pyroclastic[1] nature of the Deer Lake conglomerates as beyond any question. They represent volcanic detritus, ejected by an explosive force at the earth's surface. In this way they form a most welcome but not unexpected support to the conclusions reached in regard to the other more highly altered rocks of the same class occurring in the Marquette region.

The term "agglomerate" here applied to these rocks is one in general usage among the English geologists[2] to designate a tumultuous assemblage of volcanic ejectamenta—bombs, foreign blocks, etc., of all sizes and shapes, cemented by a fine grained paste of volcanic ash.

The closest analogues to the Deer Lake rocks are the breccias, agglomerates, and tuffs, described by Dr. A. Geikie from St. David's, in Wales.[3] This author says, p. 93:

> The rocks of St. David's present features of interest and importance, not only in the palæozoic history of Britain, but in regard to general theoretical questions. They include, for example, perhaps the oldest group of lavas and tuffs, the relative date of which is known. They have been subjected to a process of metamorphism which has affected only certain beds or kinds of rock. They have been penetrated by masses of granite and quartz porphyry, around which another kind of metamorphism has been manifested. At a later period they have been injected with diabase dikes, etc.

[1] J. J. H. Teall, Geol. Mag., London, 3d series, vol. 4, November, 1887, p. 493.

[2] Cf. J.A. Phillips, Quart. Jour. Geol. Soc., vol. 24, 1878, p. 476, and A. Geikie Text-Book of Geology, 1882, p. 163.

[3] Quart. Jour. Geol. Soc., London, vol. 39, 1883.

All this might have been written to apply equally well to the rocks occurring near Marquette.

With special reference to the tuffs, Dr. Geikie says:[1]

> They vary likewise in texture from somewhat coarse breccias or agglomerates, through many gradations, into fine silky schists in which the tufaceous character is almost lost. Generally they are distinctly granular, presenting to the naked eye abundant angular and subanglar lapilli, among which broken crystals of a white, somewhat kaolinized feldspar and fragments of fine grained felsite are often conspicuous.

The matrix of these Welsh agglomerates appears to be generally green, while the included lapilli or "pebbles" are sometimes basic in character and of a greenish color; sometimes more acid, with a compact structure and pinkish color.

Their resemblance is thus seen to be very close to the Deer Lake agglomerates described in this chapter.

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[1] Quart. Jour. Geol. Soc. London, vol. 39, p. 295.

CHAPTER VI.

GENERAL RESULTS AND CONCLUSIONS.

ORIGINAL CHARACTER OF THE MENOMINEE AND MARQUETTE GREENSTONE AREAS.

In speaking of the geology of the Menominee and Marquette regions I refer, it must be understood, only to the greenstones and certain intimately associated acid rocks. No attention was paid to the quartzites, dolomites or shales of the younger, iron-bearing Huronian. With a view of obtaining a clear idea of the primary nature of these rocks we shall consider in succession: The evidence of their eruptive character; their original types and mineralogical composition; the conditions under which they were formed; and, finally, their succession in time.

EVIDENCE OF ERUPTIVE CHARACTER.

Field evidence.—This is more distinct in the case of the Menominee greenstones on account of the simpler character of their exposures. Here we find them extending in two comparatively narrow and nearly parallel bands for a considerable distance. Their color, weight, texture, and frequent massive structure are such as are associated with rocks of igneous origin, while in some cases, as just below the Lower Quinnesec Falls, they project out of the surrounding schists in the form of a high, precipitous ridge, suggestive only of a great dike. Although successive layers of these rocks differ considerably in composition, and though they possess within themselves well marked schistose varieties, yet they are sharply defined against the adjoining Huronian beds, into which they never pass by gradual transitions. Indeed, these rocks have been considered by many of the geologists who have examined them most carefully as of eruptive origin. Those, on the other hand, who have regarded them as either wholly or partially sedimentary have been able, as far as I know, to cite only two arguments in favor of their opinion. These are: First, the coincidence of the direction of these bands, and of their alternating component members with the general strike of all the rocks of this region; and, second, the frequent conformity of the schistose structure in these bands to the bedding of the adjacent sediments.[1]

Let us, however, consider whether these two facts are not wholly in accord with the supposition that these greenstones are of igneous origin.

[1] This conformity is by no means universal.

If they were intrusive they would follow in their course the line of least resistance, which would probably be the direction of the bedding of the sediments. If, however, as seems from various considerations much more probable, these greenstones belong to a formation older than the Huronian, and if they were produced in the form of great igneous (and perhaps submarine) overflows which composed the bottom of the basin in which the iron-bearing sediments were subsequently deposited, then the great lateral compression, which so contorted these sediments and elevated them into their present almost vertical position, would have brought the underlying greenstones at the same time into just the position they now occupy. And if these greenstones had been formed as successive flows, differing more or less in structure and composition, in the process of upheaval they must have behaved like any other complex of horizontal beds and have produced conformable members of the series exposed in the Menominee valley, as is actually the case.

Now, also in regard to the second point of objection, if we admit that massive rocks may have a schistose structure (like a slaty cleavage), developed in them by pressure, then, in this case, the direction of this cleavage, perpendicular to the action of the pressure, must agree with the stratification of the now almost vertical sediments.

Nor is it necessary to assume that the schistosity of these rocks was wholly produced at the same time with the crumpling and slaty cleavages of the overlying detritals; since the same crumpling force may have worked in the same direction at two widely separated periods. Indeed, there is excellent reason to believe in two such periods, since the dikes, which in the Marquette region penetrated the greenstone schists subsequent to their being made schistose, have evidently themselves been subjected to further squeezing. These dikes appear to be contemporaneous with the sheets of greenstone interfolded with the detrital iron-bearing strata, which sheets themselves show a similar degree of schistosity with the dikes referred to. In the Marquette region there is generally a very noticeable difference as to the amounts of secondary cleavage in the greenstone-schist area, and in the strata of the overlying iron-bearing series, this being very much greater in the former case. Coincident with this difference is the frequent gentle bowing of the iron-bearing strata in this region, the dips of its layers being often quite flat, while the cleavage of the green schists always stands at a very high angle. In the Menominee region, on the other hand, the folding of the iron-bearing series is very much closer and slaty cleavage is much more generally developed. This would seem to indicate that the second period of squeezing was more intense in the Menominee area, and that it was, therefore, probably more instrumental in rendering the greenstones schistose here than in the Marquette region.

The arguments used by the defenders of the sedimentary origin of the Menominee greenstones can not therefore be regarded as valid.

On the other hand we may cite, as positive evidence that the foliation

of the greenstones is a secondary feature, the fact stated by Major Brooks, that at the Four-Foot Fall this foliation is conformable to the adjoining clay-slate, which has a "strong cleavage and no distinguishable bedding planes."[1] Thus the schistose structure of the greenstone now agrees with the secondary slaty-cleavage of the sediment, which, of course, may or may not agree with its original bedding, since this is here obliterated. Furthermore, what foliation the greenstones possess may be traced in almost every case into a jointing, or into bands produced by the crushing attendant upon faulting and slipping, which has taken place within the rock-mass. Finally, the abruptness with which the foliation of the greenstones commences and breaks off in the direction of the strike is wholly inconsistent with the theory that it is due to original stratification. At the Four-Foot Fall, for instance, the greenstones strike almost at right angles to the river, and yet they are very schistose on the Wisconsin and very massive on the Michigan bank. Such cases are not uncommon while even more difficult to explain are differences in the strike of schistose bands which traverse a massive rock (like those observed at the Upper Twin Fall), unless we assume that they were produced by a force which acted unevenly and not in a constant direction.

The field evidence that the greenstones within the Marquette belt are of igneous origin is not so plain as that encountered in the Menominee valley. Although we find here unmistakable dikes of unaltered diabase and others of altered though still massive greenstone, yet some of the most important of these rocks, especially in the northern part of the Marquette area, are so regularly banded and stratified that we are obliged to seek the agency of water to account for their formation. Nevertheless, we are not obliged to separate even these greenstones altogether from the igneous rocks which accompany them. For reasons stated at length in Chapter IV, they may be most satisfactorily explained as tuff deposits, half volcanic, half sedimentary, which throw important light upon the physical conditions under which the more massive rocks were produced.

Strong collateral evidence respecting the original nature of the greenstones of both these areas may be obtained from a study of the acid rocks which are quite constantly associated with them. The indications of the eruptive character of these rocks are so unmistakable that it seems to have hardly ever been doubted by any one who has examined them. Large areas of granite occur on each side of the Huronian basins, both in the Menominee valley and near Marquette, and dikes and apophyses, presumably radiating from these main masses, penetrate the greenstones for a considerable distance (cf. the Upper Quinnesec Fall, Horse Race, and region just north of Marquette). Now, the composition of these acid rocks is such that they resist chemical alteration much more successfully than those of a more basic character. Hence we should

[1] Geol. Wisconsin, vol. 3, p. 475.

expect to find their distinctively eruptive features, such as dike-form, line of contact, original structure, etc., much better preserved. This is the case, and yet these eruptive rocks often present phenomena of secondary foliation quite identical with those seen in the greenstones.

Near the southern end of the Brook Section, just west of Marquette, this intrusive granite is filled with fragments of the surrounding schist which it tore off while yet in a molten state. At the lower end of the Horse Race Rapid, on the Menominee River, the acid dikes show a marked diminution in the size of the grain toward the dike walls, a structure eminently characteristic of rocks which have crystallized in fissures. Near Upper Quinnesec Falls also was discovered a rock closely resembling a granitic hornfels (No. 11064). But in spite of all the evidence that the acid rocks are eruptive, their dikes, for the most part, follow the strike of those through which they break, since this is the line of least resistance, while many of them have a perfect foliation and even a gneissic structure. What we may regard as satisfactory proof that this foliation is a secondary feature may be seen at the head of the Horse Race, where it conforms to the general strike of the surrounding greenstones, even where this does not coincide, as is exceptionally the case, with the sides of the acid band (see p. 115). A similar structure has been observed by Prof. Ch. E. Weiss, of Berlin, near Thal, in Thuringia;[1] and, like the present case, it may be regarded as certain evidence that a schistose or even a banded structure may be developed in acid dikes by secondary causes, independent of their own direction, but conformable with the strike of the surrounding rocks.

Microscopical evidence.—The most convincing proof that the rocks of the Menominee and Marquette greenstone areas are of igneous origin is not to be derived, however, from their field relations, but rather from their microscopical structure. It is true that there are many cases where rocks of widely dissimilar origin resemble one another so closely that not even the minutest study of their internal structure is able to distinguish them with certainty; nevertheless there are in other cases well marked peculiarities of structure which may be regarded as unfailing indications that the rock possessing them has crystallized out of a molten magma.

An explanation for these facts is not difficult to find. The original structures of clastic and igneous rocks are characteristic and essentially distinct. Where these remain there is no danger of confusion. In the process of metamorphism, however, there is a constant tendency to obliterate the original features and to substitute for them certain secondary features. But these latter depend altogether upon the chemical constitution of the mass and the nature of the metamorphosing forces, and are independent of both the mineral composition and the structure of the original rock. Hence it is that rocks fundamentally distinct in

[1] Petrographische Beiträge aus dem nördlichen Thüringer Walde. Jahrbuch preuss. geol. Landesanstalt für 1883, pp. 213–237. Berlin, 1884.

both origin and structure grow more and more alike when subject to metamorphism. They may finally become indistinguishable and thus their life histories may be lost, but so long as any trace of the original structure is recognizable it may be relied upon as a safe guide.

It is, therefore, a matter of prime importance in petrography to be thoroughly acquainted with original rock structures, and to understand their significance. As a rule, those found in igneous rocks are more unmistakable than those which characterize clastic deposits. For instance, universal observation, together with numerous synthetical experiments in the laboratory, has shown that the peculiar divergent radial structure, known as the "ophitic" or "diabase" structure, is always the product of crystallization from a molten mass of certain basic rocks. No single observation has ever been made to indicate that this structure can originate in a sediment or by any metamorphism of a sediment; hence, we are justified, when we encounter the "ophitic" structure in a rock (no matter how much it may otherwise resemble a sedimentary deposit) in assuming that it is of igneous origin. Now, precisely this characteristic structure is what we do meet most frequently in the greenstones of both the Menominee and the Marquette area. Nor is it alone in the most massive and apparently least altered specimens that it is found; often the most perfectly schistose of these greenstones disclose it, and that, too, where none of the mineral components have escaped complete alteration.

Other structures, scarcely less typical of an igneous origin are also encountered in other of the Marquette and Menominee rocks. Some of these are: *porphyritic structure*, with well defined crystals and even a zonal growth; *micropegmatite and granophyre structure*, in granite, diorite and diabase; *poicilitic structure*, shown by the hornblende in the diorite porphyry at Lower Quinnesec Falls. The skeleton forms of the acicular feldspar crystals, still recognizable in the aphanitic greenstones of the Upper Twin Fall, as well as in those of the southern Marquette and Negaunee areas, are also strongly indicative of igneous, and perhaps also of glassy rocks.

The evidence of eruptive origin afforded by the present mineral components of the Marquette and Menominee rocks is not so satisfactory as that based on their structure. Nor is this different from what we should expect. Chemical metamorphism precedes structural metamorphism. Instances are frequent in both regions of the disappearance of every original mineral, while the structure remains intact. If we except the comparatively recent and unaltered diabases near Marquette, pyroxene—that most characteristic of volcanic minerals—was hardly ever encountered except in the gabbro at Sturgeon Falls. We can, however, assert with certainty that it was once present in many other rocks, where it is now represented by the pale green hornblende into which it so readily passes. Other species typical of igneous rocks, such as lath-

shaped labradorite crystals and ilmenite fringed with leucoxene, on the other hand, are still met with in abundance.

With such evidence that the greenstones and associated acid rocks of the Menominee and Marquette regions are igneous in their origin, we may next inquire as to how many different types may still with certainty be recognized among them. In this section, whose effort it is to reconstruct the original form of the greenstones, no reference will be made to the secondary or metamorphic rock-types.

DIFFERENT ORIGINAL ROCK-TYPES.

BASIC ROCKS.

Olivine Gabbro.—This type, containing abundant and perfectly crystallized olivine, was found only in the northern area above Negaunee; (See Chap. V, p. 180); and even here under circumstances which left doubt as to whether the exposure was in situ, or a part of a huge, buried glacial bowlder.

Gabbro.—The only undoubted representatives of this type, i. e., granular aggregates of allotriomorphic diallage and plagioclase, were found at Sturgeon Falls on the Menominee River. Their diallage is of an unusually pale color and, like the whole rock, remarkably poor in iron, (cf. analysis on p. 76.) Their feldspar is almost wholly changed to saussurite. The rock exposed near the Eureka shaft, two miles west of Marquette, appears once to have belonged to this same type (p. 70); while the granular diorites so common at the Quinnesec Falls, although they now contain only pale green hornblende and no diallage, agree so closely with the Sturgeon Falls rock in appearance, structure, and chemical composition, that it is very probable that they were once gabbros also (pp. 86, 102).

Diabase.—This is by far the most common rock-type and it is found in every variety and stage of alteration.

An unaltered olivine diabase is the youngest rock of the Marquette area. It intersects all the other greenstones as well as the granite, as may be seen at the mouth of Dead River, besides occurring in interbedded sheets in the iron-bearing series itself. It forms the great dike which terminates at Lighthouse Point, as well as many other smaller ones exposed in the Brook Section, in the northern area and at other localities. As the olivine is the first of all minerals to disappear, this type can, of course, be recognized only in the freshest specimens.

It is not always possible to say positively whether the quartz in the diabase is an original or a secondary constituent. The former, however, is probably the case in certain very fresh specimens and where, as in No. 11675 from the great dike, and No. 11646 from Front street, Marquette, it is present as a micropegmatitic intergrowth with the feldspar (p. 141).

No non-olivinitic diabase was discovered in a perfectly fresh state, but this type is assumed for many occurrences in which alteration is more or

less advanced. Such an assumption must, however, be doubtful, since any original olivine would have been the first mineral to disappear.

Diabase Porphyry.—It is now impossible to say whether the porphyritic greenstones occurring at the western end of the ridge below the Lower Quinnesec Falls once belonged to this type or not. If they did, they contained considerable original brown hornblende as an accessory constituent; but it seems more probable that these rocks were diorites.

Glassy Diabase and Melaphyre.—From the sides of the unaltered diabase dikes, glassy and half glassy rocks were obtained, which, of course, represent only a local facies of the main mass, due to more rapid cooling. They contain incomplete and skeleton forms of the minerals which were the first to crystallize, and in this respect they closely resemble some of the aphanitic greenstones of the southern Marquette and Negaunee areas. Indeed, one of these half glassy rocks from the edge of a much altered dike in the Brook Section, near Marquette (No. 11680, see p. 144), is quite identical with a certain widespread variety of the fine grained greenstones, and gives perhaps the clew for the deciphering of their original form (cf. p. 163).

Diorite.—The readiness with which the pyroxene of eruptive rocks passes over into a corresponding amphibole, makes the number of diorites among the Menominee and Marquette greenstones appear much larger than it really is. A majority of these are undoubtedly of secondary origin, having been derived from pyroxene rocks. Nevertheless, others of them, in which the secondary hornblende can be traced back into a compact brown variety of the same mineral, must be regarded as true diorites, unless we make the assumption that pyroxene has passed by paramorphism first into basaltic, and subsequently into fibrous green hornblende. The origin of other of the dioritic greenstones must always remain uncertain. Even at the risk of including some rocks of secondary origin, the principal dioritic types may be enumerated as follows: *Gabbro type*—light colored, granular rocks, like those forming the barrier at Upper Quinnesec Falls; these so closely resemble the Sturgeon Falls gabbro (even down to the orthopinacoidal parting of their hornblende) that there is strong reason to believe that they have been derived from a similar rock. *Coarse grained diorite* of the Horse Race, with idiomorphic feldspar and a pale green hornblende, which, though itself secondary, has probably been formed from a compact variety of the same species. *Granular diorite,* like No. 11175 from Four-Foot Falls and several dike-rocks in the Negaunee and Northern areas. *Quartz diorite,* like the Picnic Island rock and No. 11831, from the Northern area, west of Marquette. (See Plate IX, fig. 2.) Both of these are perhaps more properly amphibole granites, although the relative proportions of their orthoclase and triclinic feldspar leaves this in doubt. The so-called "epidiorites" are undoubtedly of secondary origin, and have been derived generally from augitic rocks.

Diorite Porphyry.—The rocks containing large poicilitic hornblende crystals, collected from the western end of the ridge below the Little Quinnesec Falls, which have already been mentioned under the head of Diabase Porphyry, although they should perhaps receive the above designation.

Tuffs.—The schistose, banded greenstones which compose so large a part of the northern Marquette area are found to be best explained as tuff deposits of the basic eruptives which accompany them.

ACID ROCKS.

Granite.—Each of the greenstone areas is bounded on both the north and south by a large mass of granite. This rock is a typical *granitite* as can be best seen from the specimens collected south of the Horse Race in the Menominee Valley and north of the Marquette greenstone belt. *Muscovite granite* occurs in some of the bosses near Marquette, notably at the so called "gold mine" near Pine street. *Amphibole granite* is possibly represented in the specimens from Picnic Islands and the Northern area which have already been mentioned under the head of Quartz Diorite, although they appear to occupy a position midway between these two types.

Granite Porphyry and Quartz Porphyry are the forms assumed by the granite where it penetrates the greenstones in dikes or apophyses. They are abundant in both areas and are united by a continuous series of transitional forms. These rocks are among the most interesting ones anywhere met with on account of the perfection with which they show the effects of dynamic action. By either stretching or compression they are changed into Augen gneiss or schistose porphyry, both of which retain in their microscopic structure very plain evidence of the manner in which they were produced.

ORIGINAL MINERAL CONSTITUENTS.

Orthoclase occurs in all the acid rocks—granites, and porphyries; in some of the fragmental rock, as, for instance, those near Iron Mountain and in the stretched tuffs on the Carp River north of Teal Lake, and probably in the Picnic Island rock north of Marquette.

Microcline.—It is doubtful whether this form of potash feldspar is ever original. In some cases at least it is certainly the result of intense dynamic action on rocks already solid.

Oligoclase is, in all probability, the species of striated feldspar occurring in the granites.

Labradorite is the prevailing original feldspar in all the greenstones, as it is in the unaltered diabases occuring near Marquette.

Quartz is an abundant component of all the acid types; and it occurs also in both diorites and diabases, although it is here not always possible to distinguish between what is original and what is secondary.

Muscovite seems to exist in one or two granites as a primary component, but in the majority of cases it is a derivative of the orthoclase.

Biotite is abundant in the granites. It is also present in the diorites, especially in those from the Horse Race Rapid, although here it may be secondarily developed out of the hornblende. In the diabase it is sometimes seen forming a border around the ilmenite.

Hornblende.—Compact brown, or basaltic hornblende is common in very many of the greenstones, though mostly as remnants of crystals which have become partly green or fibrous. It is also present in the Sturgeon Falls gabbro and in the Marquette olivine diabase. Compact green hornblende is also a very common mineral in the greenstones, but it impossible to tell to how great a degree this may be of secondary origin.

Diallage of a very pale color and very poor in iron is abundant in the gabbro of Sturgeon Falls. (See Pl. VIII, fig. 1.)

Augite of the ordinary kind, having a reddish brown color in transmitted light, is an essential ingredient of all the fresher diabases; and often exists as a core in the center of partially uralitized crystals.

Olivine, in fresh and perfectly formed crystals, was found in the olivine gabbro of doubtful origin which occurred in the Northern area above Negaunee. It also once formed a component of the younger diabases near Marquette, although it is now so altered to serpentine as to be only recognizable by its form.

Zircon is abundant in nearly all the acid rocks, and is present in the sediments near Iron Mountain in the Menominee valley. (No. 11113.)

Apatite is universal in all the rocks which have not been sufficiently altered to obscure it.

Tourmaline is common in the more acid rocks. It may be best seen in the granite and acid dikes near the Horse Race and Upper Quinnesec Falls. It is also present in the sediments exposed near Iron Mountain and Four-Foot Falls, as well as in the hornfels (No. 11064.)

Sphene occurs in both granite and diorite, especially in association with hornblende. In some instances it seems to have been derived from the alteration of ilmenite.

Orthite (*Allanite*) is present in certain granites, both near the Horse Race and in the Northern area above Negaunee.

Ilmenite and Magnetite.—The opaque iron oxide minerals are present in all the rocks in their usual abundance. Ilmenite is the most frequent, especially in the greenstones, but magnetite is also present.

CONDITIONS UNDER WHICH THE GREENSTONES WERE FORMED.

There is considerable evidence to show that the greenstones, both of the Menominee and the Marquette region, solidified at the surface, under subaerial or subaqueous conditions.

In the Menominee Valley this evidence consists (1) of the fine texture of the rocks; and (2) of the alternation of bands of different types, which probably in their original position represented successive flows. Fineness of grain is universal in the Menominee greenstones, and we may be certain that it was a primary feature in spite of the extensive alter-

ation of these rocks. It is especially noticeable in the case of the gabbro, which is almost always a coarse grained rock when it has solidified at any depth. The succession of massive beds, like the pale gabbros and the dark diabases seen at Lower Quinnesec Falls, are difficult to account for except by supposing that they were once horizontal sheets which flowed one over another and which were subsequently elevated into their present nearly vertical position. Traces of tuff material are not as distinct here as in the Marquette region, although indications of their existence are by no means wanting. We might reasonably expect that any original scoriaceous or amygdaloidal structure would have disappeared in the course of the profound chemical changes through which these greenstones have passed.

In the Marquette area proof of the superficial origin of the greenstones may be found (1) in the fineness of grain, and (2) in the fragmental detritus or tuff, such as would accompany volcanic action. The so-called "aphanitic greenstones," which play so important a role in the southern Marquette and Negaunee districts, have traces of a structure like that of a porphyrite or melaphyre (see Pl. X, fig. 2). At least there are incomplete forms of feldspar crystals apparently imbedded in a groundmass which might easily have originated from the devitrification and decomposition of a cryptocrystalline or even glassy base. The finely banded greenstone schists occupying the northern portion of the Marquette belt present such strong evidence of stratification and such peculiarities of microscopic structure (see Pl XVI, fig. 1) that they are best explained as tuff deposits belonging to the massive basic rocks. The presence of fragmental material of this kind, of course, strongly indicates surface origin for all these greenstones. Still other signs point in the same direction. At least one well marked specimen of amygdaloidal structure (No. 11746) was found near Baldwin's Kilns, but in the present highly altered condition of these rocks it can only occasion surprise that even this was preserved.

MACROSTRUCTURAL METAMORPHISM OF THE MENOMINEE AND MARQUETTE MASSIVE ROCKS.

This embraces all modifications in the structure of the massive rocks produced by dynamic agencies and plainly visible to the unaided eye. Such changes consist for the most part in the production of a banding, foliation, or schistose structure, which tend to make the eruptive rocks resemble stratified deposits. They are a secondary feature and must be correlated with the slaty cleavage, not with the original bedding of sediments.

Inthe process of upheaval and folding rocks may be subjected to great compression, with more or less attendant shearing or faulting, or the reverse may be true and a tension result. In the first case foliation is produced; in the second, the phenomena of stretching.

MACROSTRUCTURAL METAMORPHISM THROUGH COMPRESSION, FAULTING, OR CRUSHING.

Simple compression.—There seems to be no doubt that a foliation or slaty cleavage may be produced by pressure in massive as well as in stratified rocks. This cleavage is developed in all cases at right angles to the direction of the pressure. It is particularly frequent in such basic eruptive rocks as, by their chemical composition, are more subject to alteration. In these the secondary development of such cleavable minerals as chlorite, hornblende, sericite, and biotite, which are given a parallel arrangement by crystallizing under pressure, strongly conduces to the production of a schistose structure. The pressure accelerates the chemical action, and may in this way develop a schistose out of a massive rock without movement in the mass.

A very general feature in the foliated greenstones of both the Menominee and Marquette regions is their tendency to cleave parallel to a line instead of parallel to a plane; in other words, they possess a dip but no decided strike. The rock then breaks with readiness into long rhomboidal prisms with almost any angle, but is severed with difficulty at right angles to this axis of foliation. Such a structure would seem to indicate the action of an unequal or shifting pressure. Examples of this method of parting are very common, especially at Sturgeon, Lower Quinnesec, and Twin Falls, in the Menominee Valley, and in the southern portion of the Marquette greenstone area.

One of the best proofs of the secondary origin through dynamic agency of the greenstone foliation is the fact, noticed by Major Brooks, that at Four-Foot Falls this is parallel to the slaty cleavage, but not to the bedding of adjoining sediments.

Another method by which a schistose structure is produced in the Menominee greenstones, is the gradual flattening of the rhomboidal prisms which are formed by the intersection of two sets of joint-planes. This is illustrated by Figs. 20, 21, and 22, on page 128. These prisms seem to be elongated by the action of intense pressure into a series of interlacing lenses. A sort of "Flaser" structure is thus produced which, in its extreme development, becomes a well characterized schistose structure. Even in the broadest of these prisms a latent cleavage is often noticeable parallel to their longest diagonal, always following the general strike of the adjoining rocks. This structure, which I have designated as rhomboidal, or diamond parting, may best be seen at the Twin Falls or at the upper end of the great greenstone ridge below Lower Quinnesec Falls.

Faulting or crushing.—A schistose structure is always produced in massive rocks along lines where a great tension has been relieved by breaking and a consequent displacement. Movement of this kind within a solid mass, must be accompanied by more or less intense crushing, and this allows increased circulation and hence of the rapid production of secondary crystallizations. Admirable instances of this phenom-

enon abound in both the Menominee and Marquette greenstones. At the Sturgeon Falls, along the basin just below Lower Quinnesec Falls, below the Horse Race, at the Twin Falls, at the foot of Arch street, Marquette, and at many other localities within this area, it may be seen with remarkable distinctness. The exact effect of the crushing on the original mineral constituents is visible only under the microscope and hence will be considered in the succeeding chapter; but any one who will carefully examine any of the above named localities can not fail to be convinced of the continuity and original identity of the massive and schistose rocks.

Both the width of these schistose bands and the intensity of the crushing which they exhibit vary widely in different cases. Their direction almost always coincides with the general strike, although at Upper Twin Falls such bands were observed to have a different direction. (See p. 132.)

This pulverization of the rock is accompanied by greatly increased chemical action (except in the notable instance of the feldspar) and the abundant production of chlorite. Such crushed bands possess a more or less perfect lenticular or "Flaser" structure, which passes gradually into a lamination where the action has been more intense. This is almost entirely due to the parallel arrangement of the secondary chlorite scales, so that we have a basic eruptive rock developing into a typical chlorite schist.

Excellent examples of a massive, though much altered greenstone fraying out into a chlorite schist by the action of a shearing force along lines of slight displacement, were found at lower Twin Falls, and are illustrated in Figs. 23 and 24. (See pp. 129, 130.)

The great mechanical force generated in the course of orographic movements, aided by chemical action, sometimes develops schistose bands in massive rocks, which wind around and encircle compact cores. These are spheroidal or lenticular in shape, and seem for some unknown reason to have better resisted the metamorphosing influences. A fine example of this kind may be seen on the Wisconsin side of the Menominee River, just at the foot of Lower Quinnesec Falls. It is represented by specimens Nos. 11017 to 11020, described on p. 93. Other examples of the same kind occur in the railroad cut near Front street, Marquette.

This last described structure has much in common with the spheroidal or lenticular parting observed in the aphanitic greenstones of the southern Marquette and Negaunee areas. (See Figs. 26 and 27, pp. 166, 177.) Near the mouth of Whetstone Brook; in the neighborhood of Baldwin's Kilns, and between Teal Lake and the Carp River, we see the fine-grained greenstones broken up into circular or oval areas, which are separated by a finer schistose matrix. This structure is common through the Northwest, and has been termed by the Canadian geologists "concretionary trap." It is, however, in no sense really concre-

tionary, but must be ascribed either to contraction which frequently produces a perlitic structure or spheroidal parting in volcanic rocks, or to a mechanical brecciation and rubbing together of the disjointed fragments, as was found by Rothpletz to be the case in similar greenstone schists of Saxony. (See p. 167.)

MACROSTRUCTURAL METAMORPHISM THROUGH STRETCHING.

The effect of stretching upon rock masses has only recently come to engage the attention of geologists. It is evident that in the process of the upheaval or folding some parts of the mass must be strained, while other parts are compressed. As Heim first pointed out, such a tension is relieved sometimes with and sometimes without a visible rupture. Both of these methods are well illustrated in the massive rocks of the Menominee and Marquette regions.

In the first case we find the formation of irregular, ragged seams, which Heim has designated as gaping rents ("klaffende Risse"), and which I have termed "cross-gashes," from their being torn open in a direction perpendicular to that in which the tension was exerted. They are, therefore, approximately parallel, and may produce a rough sort of schistose structure. These seams sometimes remain open, but are sometimes filled with secondary crystallizations, like quartz, calcite, or chlorite, often with epidote. They are best exhibited in the great greenstone ridge which extends along the river's left bank below Lower Quinnesec Falls. Their appearance, as far as it can be shown in a hand-specimen, is represented in Fig. 10, p. 81.

The manner in which the round cores of the spheroidally parted greenstones in some cases have been drawn out into interlacing lenses, has already been noted (p. 177).

Stretching action may sometimes produce a banding in massive rocks. This is especially the case with acid types, like granite and quartz porphyry. Examples of this are to be found among the acid dikes near the Horse Race and in the vicinity of Marquette, but the most indubitable evidence of stretching in these rocks is contained in their microscopic structure, and must therefore be reserved for description in the following section.

MICROSTRUCTURAL METAMORPHISM OF THE MENOMINEE AND MARQUETTE MASSIVE ROCKS.

Where profound mechanical and chemical changes have gone on simultaneously in rock masses, the final product may be wholly different from the original starting point. Sedimentary and eruptive rocks seem to approach each other more and more nearly, the longer they are exposed to the same metamorphosing influences. In many cases the derivation of certain schists can never be definitely settled; in other cases, however, where the field evidence is insufficient to decide, the micro-

scope may yield reliable data for settling the origin of doubtful crystalline schists. Characteristic minerals or structures may often be detected under the microscope after every original feature visible to the unaided eye has been obliterated.

In stating the results of dynamic action observed with a microscope in the Lake Superior rocks, we may speak first of the effect upon individual minerals, and then of new structures produced. As a rule, those minerals and rocks which are hardest and most brittle are found to exhibit these mechanical effects most perfectly.

EFFECTS OF DYNAMIC ACTION ON INDIVIDUAL MINERALS.

Quartz.—We find corroborative evidence of the fact stated by others that quartz is frequently more sensitive to pressure than feldspar. In the quartz porphyry, No. 11707, for instance (see Pl. XV, fig. 2), which has undergone a violent stretching, the feldspar crystals apparently exhibit no resultant phenomena, if we except the presence in their center of microcline as a possible product of strain; the quartz crystals, on the other hand, show an unusual amount of deformation. In some cases they are pinched out into pear or spindle shaped areas with an undulatory extinction; while in other cases they are much more elongated, but show that this result has not been reached without a crushing and displacement of their original substance (granulation). The fragments are converted into a mosaic of interlocking grains by the readiness with which silica is dissolved and deposited. Quartz that is more or less optically disturbed is almost universal in the acid rocks examined, showing that hardly any of them have been entirely free from mechanical strains. That the quartz grains in the granite No. 11104 are not all original is proved by the little tourmaline crystal, which is fractured and faulted at the junction of two of them, as depicted in Fig. 13, p. 112.

Feldspar.—The first effect of strain on feldspar is to produce an undulatory extinction. This cannot, however, be carried as far as it is in quartz, because the tension is here able to relieve itself by molecular movements and the consequent formation of twinning lamellæ. Several cases were encountered where the gridiron or microcline structure appears to have been secondarily developed in a potash feldspar by this means, as in the granites Nos. 11104 and 11710 and in the schistose quartz porphyry No. 11707. Such a production of secondary or strain lamellæ in the triclinic feldspars is by no means unusual.

Where the mechanical action is too intense to produce mere optical disturbance or molecular gliding without rupture, the force of cohesion is entirely overcome and the feldspar is fissured or crushed. In case the force is exerted as a tension, the fragments thus formed are separated, and the spaces between them are filled with secondary crystallizations, especially chlorite. In other cases the fragments are merely faulted against one another. Such examples of stretched and faulted feldspar are very abundant in the schistose greenstones and acid rocks

of the Menominee and Marquette districts. It is generally possible to recognize what fragments once belonged together, as may be seen by an inspection of Pl. IX, fig. 2, Pl. XI, fig. 2, Pl. XIV, figs. 1 and 2, and Fig. 11 on p. 105. Even in very schistose rocks, which are in other respects chemically much altered, these broken feldspars are, as a rule, unexpectedly fresh; a fact which will receive particular attention in the succeeding section.

If the mechanical force is still greater, a pulverizing or granulation of the feldspar ensues. This is always accompanied by chemical action, consisting of more or less complete solution and recrystallization. In this way the substance is molded into new forms, which accord better with the existing strains.

Such a partial granulation of a large porphyritic feldspar crystal, producing one of the lenticular "Augen" of the metamorphic gneisses of the Horse Race, is shown in Pl. XV, fig. 1.

In the process of feldspar granulation the calcium is frequently removed, and the secondary mosaic is largely composed of albite, as was first shown by Lossen.

Pyroxene.—Diallage is very subject to mechanical deformation. On account of its relative softness and flexibility this consists mostly of the bending or twisting of the crystals, or in the occasional production of twinning lamellæ. These phenomena may be well seen in the almost colorless diallage of the Sturgeon Falls gabbro. Pyroxene exists in no other of the rocks examined except in those which are too young to show any effects whatever of dynamic action.

Hornblende.—Certainly in a large majority and possibly in all the rocks which I have studied from northern Michigan, hornblende is a secondary product; since, then, it is a result of metamorphism, it is not strange that we rarely see in it the effects of that mechanical action which caused the metamorphism.

Mica.—On account of its flexibility mica, like diallage, would be well fitted to exhibit mechanical phenomena; but the fact that, like the hornblende, it is mostly a secondary mineral in those rocks to which we have here devoted our attention, prevents such deformations from being common.

Zircon, Tourmaline, etc.—These minute products of the first crystallization in the rock are often found to be broken or faulted by mechanical action, as is shown in Fig. 13, p. 112, and Fig. 18, p. 122.

Ilmenite.—The iron minerals, on account of their opacity, of course can exhibit no optical disturbance, but their grains are frequently torn apart just like the feldspar crystals. This has been described in numerous instances, and it is represented in Pl. XI, fig. 2.

NEW STRUCTURES PRODUCED BY DYNAMIC ACTION.

Whenever the crushing of rocks by dynamic agencies is accompanied, as it almost always is, by chemical action and the production of new minerals, these must arrange themselves in accordance with the exist-

ing strains. These secondary minerals are such as themselves possess a very perfect cleavage; their production, therefore, under circumstances of uniform and continued strain, will naturally impart a foliation to the originally massive rock. Nor is this all. The relief of the strain and the consequent crushing of the rock will take place along certain planes much more completely than along others; hence in these planes the secondary minerals will be more abundant, and a banding of a once homogeneous rock may result.

The final structures produced in this manner depend not altogether upon the force exerted, but also upon the primary structure of the rock.

The rubbing together of individual crystal grains, the adhesion between which is weaker than their own internal cohesion, may produce a pulverizing only around the edge, when the force is not too intense. This phenomenon, to which Professor Kjerulf has applied the term "peripheral granulation" (randliche Kataklase),[1] may bring about a sort of pseudo-porphyritic structure, in which, however the porphyritic crystals are only the larger remnants of the former grains without a crystal form of their own; or, if the crushing has been less, the grains may appear to be held together by a fine granular cement, like the stones of a wall by their mortar. Hence Professor Törnebohm has spoken of this as the "mortar structure" (Mörtel Structur).[2] Many admirable examples of these structures are to be seen in the Menominee and Marquette rocks, especially in those of an acid character. There may be particularly mentioned the granite from the great area south of the Menominee, No. 11104; Nos. 11189 and 11190 from acid dikes at the Horse Race; Nos. 11678 and 11710 from the Brook Section, near Marquette. In the first instance, a distinct micropegmatitic structure is a noticeable feature of the granular cement.

If the original structure of the rock was porphyritic instead of granitic, we find corresponding differences in the result. The groundmass is made schistose by the development out of its feldspar of sericite or chlorite. The porphyritic crystals are more or less granulated, but the secondary mosaic thus formed is often coarser in grain than the groundmass. This is arranged around the remnant of the original crystal in a lenticular area known as the "eye," or "Auge," in rocks called by the Germans, on account of this structure, Augengneiss. (See Pl. XV, fig. 1.) Unusually beautiful examples of this kind are to be found among the acid dikes along the shores of the Horse Race—especially specimens numbered 11184 and 11196. In some of the schists which have been derived from the Sturgeon Falls gabbros a similar structure is present.

Where secondary micaceous minerals have been developed in sinuous bands which interlace and twine about abundant oval cores, a lenticu-

[1] Grundfjeldsprofilet ved Mjøsens sydende. Nyt Mag. for Naturvidenskaberne, vol. 29, p. 215, 1885 (Neues Jahrbuch für Mineral., 1886, vol. 2, Referate, p. 244.)

[2] Några ord om granit och gneis. Geol. Fören. Stockholm Förhandl, vol. 5, pp. 233–248. (Neues. Jahrbuch für Mineral., 1881, vol. 2, Referate, p. 50.)

lar structure is produced, in which there is no contrast between groundmass and porphyritic crystals. This is called by the Germans "Flaser" structure, a term which may advantageously be transferred to the English. It is often the case that a structure of this kind is so fine as to be visible only under the microscope, when the designation "microflaser structure" is applicable. Examples of this lenticular interlacing are abundant in the schistose greenstones of northern Michigan. It is especially typical in the Sturgeon Falls schists, and in those at Lower Quinnesec Falls; it may also be well seen in the granite at the mouth of the Dead River, north of Marquette.

In rocks that have been subjected to a great tension, a peculiar microscopical structure has been developed, caused by the rupture of the original crystals and a pulling apart of their fragments. Between these chlorite is formed, the scales of which are parallel to one another and to the direction of the stretching. This chlorite appears to have resulted from the recrystallization of the substance of the original bisilicates, since no trace of these now remains, although the broken feldspar is always remarkably fresh. There must be something in the dynamic action of an intense tension particularly conducive to the formation of this chlorite, for exactly this modification of this mineral was not encountered in rocks produced in any other way. Its presence, of course, brings out a decided schistose structure. Excellent examples of this phase of structural metamorphism abound in the Menominee and Marquette greenstones, although I do not know that anything exactly like it (particularly when taken in connection with the remarkable freedom of the broken feldspar from all signs of chemical change) has ever been described before. It is illustrated in Pl. XI, fig. 2. The widely different results produced in the same greenstone by chemical action alone on the one hand, and by this agency combined with stretching on the other, are shown in Pl. IX, figs. 1 and 2. The same thing is admirably seen in two specimens (Nos. 11651 and 11652) from the Cleveland ore dock in Marquette. (See p. 168.)

If we could desire any more certain proof that these "stretching structures" are of secondary origin, developed in an already solid rock, we should find it in No. 11803 (Pl. XIV, fig. 2). Here the porphyritic feldspar crystals lie in the groundmass at every conceivable angle, showing that at the time they were formed there was no force to affect their orientation. Their breaking and tearing asunder, however, in every case, has taken place in the direction of the foliation or stretching, without the least reference to the position of the feldspar crystal itself.

MINERALOGICAL (CHEMICAL) METAMORPHISM OF THE MENOMINEE AND MARQUETTE ROCKS.

Chemical alteration may go on to almost any extent in massive rocks, unattended by any mechanical deformation; and yet certain chemical changes in rock-forming minerals seem to be dependent upon the phys-

ical conditions produced by great orographic strains. It is easy to understand how the crushing of a rock should, as a rule, accelerate chemical activity by increasing the circulation and possibly by raising the temperature by friction; but more than this, we find that of several different alterations to which a given mineral is subject, certain ones are never found except in those regions where dynamic action has been intense.

It is true that the same secondary mineral may be produced in different ways. It may result from the same original mineral under different conditions, or from different minerals under the same conditions, or from different minerals under different conditions. It may also sometimes be derived from a single substance, and sometimes from a reaction between two or more substances. On account of the small number of elements which enter into the composition of rock-forming minerals, their physical differences are due mostly to the different proportions in which these elements are combined. Very slight variation in conditions may modify these proportions and so produce one mineral or another. Even in exactly the same chemical compound, what may be a stable state under one set of conditions, may be an unstable state under another set. So delicate is this adjustment that the secondary minerals produced in a given case depend not merely upon the chemical composition of the original rock or of its constituents, but even to a greater degree upon the physical conditions obtaining at the time of their formation. Thus with every change of these, one generation of secondary minerals may give place to another.

Such a succession of alterations, each dependent upon its own set of conditions, tends to obscure the life history of a rock mass; and yet, in spite of its complexity, this study is full of promise. It is generally possible to separate the products of metamorphism proper from those of weathering, as described in Chapter I (see p. 36). All the massive rocks of the Menominee and Marquette regions offer admirable opportunity for the study of the first of these alterations, while the more basic types often present the subsequent effects of weathering.

In reviewing and summing up the results of chemical alteration already described at length, it will be advantageous first to enumerate the minerals of secondary origin, stating briefly the circumstances under which each was probably formed, and second to trace out the different phases of alteration to which each of the more important original constituents has been subjected.

SECONDARY MINERALS AND THEIR ORIGIN.

PRODUCTS OF METAMORPHISM.

Feldspar.—This mineral is not common as a secondary product except in the form of albite, which as Lossen has shown (see Chap. I. p. 60) is a very characteristic result of dynamic metamorphism. In the Sturgeon Falls gabbro albite is a common secondary mineral, both as

the base of saussurite and in the form of clear, transparent veins. Here the twinning structure is not frequent, but it may be seen in some of the veins, as is shown in Fig. 4, p. 69. Albite in the form of a fine granular mosaic, with or without quartz also occurs in many of the altered diabases. Its substance is so clear and glassy as to leave no doubt about its being a secondary product.

Microcline as a secondary mineral is to be referred rather to the effect of pressure twinning than to chemical alteration.

Saussurite (Chapter I, p. 58) is not a simple mineral, but a mixture derived from the alteration of the lime-soda feldspars. It is abundant in the more basic rocks of the Menominee and Marquette regions—in the gabbros of Sturgeon Falls and in many diabases and diorites. The base is a clear, soda feldspar (albite) which contains zoisite needles, or more rarely epidote and colorless garnet. (No. 11189, p. 108.)

Zoisite occurs only as one of the constituents of saussurite above described. It is in the form of minute needles, without terminations, as shown in Figs. 5 and 6 (pp. 69, 70). These differ much in size, and between crossed nicols display dull bluish interference colors. When the zoisite needles are very small the saussurite is a gray opaque mass, which only the highest power of the microscope is able to resolve.

Garnet was observed only once, in minute colorless crystals, forming, along with epidote, one of the constitutents of the saussurite in speci. men No. 11189. (see p. 108).

Quartz is a widespread secondary mineral. It often originates from the breaking up of the more acid feldspars, like orthoclase. It may also originate from the lime-soda feldspars. Primary and secondary quartz sometimes present an identical appearance. In some of the Lake Superior diabases quartz seems to be an original component, and in others of the more altered ones it is certainly of secondary origin. In a few intermediate cases its origin must always remain doubtful. Owing to the ease with which silica is transported in solution, that which is set free by the decomposition of the silicates is often entirely removed from the rock or is deposited in seams. In at least one instance a brown isotropic substance resembling opal was observed (the gabbro from Eureka Shaft near Marquette p. 170).

Hornblende.—Although there is reason for considering the hornblende in some of the Menominee and Marquette greenstones as a primary constituent, still there can be no doubt that this mineral is also the most important secondary component of these rocks. In a fibrous form as uralite, amianth, etc., hornblende is almost the sole representative of the former pyroxene in the more altered and schistose diabases, and the same mineral seems also to be the final metamorphic product of the compact hornblende in the diorites. Indeed, the schistose structure of these rocks is largely due to the production of fibrous hornblende and lamellar minerals of the mica type, and to their arrangement parallel to a single plane. The components of the secondary fibrous hornblende

are mainly derived from some bisilicate, like pyroxene or compact hornblende, but its position is by no means confined to the area formerly occupied by these substances. On the contrary, the material shows a tendency to wander, and to develop amphibole needles along the cleavage cracks of the feldspar, as seen in Plate XII, fig. 2. This may even become filled with the hornblende, as in the epidiorite, No. 11663, from Pine street, Marquette, and the whole rock be finally reduced to a fine, felt-like mass, as shown in Plate IX, fig. 1.

Compact hornblende also, both brown and green, appears to have resulted extensively in the greenstones from the direct alteration or molecular rearrangement of pyroxene. Such a change has often been recorded, as stated in Chap. I. Indeed, the probability that much of the pyroxene of the original rocks has passed into fibrous green hornblende *through an intermediate stage of compact hornblende* has already been alluded to (p. 72). The brown or basaltic variety is to be found associated with the diallage of the Sturgeon Falls gabbro, as shown in Pl. VIII, figs. 1 and 2; also in the porphyritic rock from the western end of the "gabbro ridge," near Little Quinnesec Falls, on the Menominee. The compact green hornblende of Nos. 11176 and 11178, from the Four-Foot Fall, and of many of the Horse Race diorites, has precisely the form of diabasic augite; and in spite of its compact structure shows in its pale color and darker green border clear evidence of its secondary origin.[1] The pale compact hornblende of the barrier rock at Upper Quinnesec Falls (No. 11054) looks exactly like diallage,[2] and under the microscope its most exceptional orthopinacoidal parting bears testimony to its derivation from this mineral. (See p. 103.)

The manner in which the compact hornblende ravels out and becomes fibrous is often clearly seen in the Lake Superior greenstones, and is shown in Pl. XII, fig. 1, and in Fig. 19 on p. 126.

Epidote is a common metamorphic mineral, and appears almost always in small but well formed yellowish crystals. It sometimes forms one of the constituents of saussurite, but far less frequently than zoisite, as more iron is necessary for its genesis. In one case, No. 11091, the feldspar of a coarsely granular rock from the Horse Race, seems wholly changed to large individuals of epidote, while the pyroxene has given place to corresponding areas of a rather compact greenish hornblende (p. 108). In No. 11712, from the Brook Section, near Marquette, the change of the feldspar to epidote is less complete. Epidote more commonly results from the alteration (perhaps weathering) of some ferrous bisilicate. Here it is generally in association with bright green chlorite in the form of the characteristic aggregate described in Chap. I (p. 56). This is very common in many of the more altered greenstones of the regions studied. (See Pl. XI, fig 1.)

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[1] See Pl. XII, fig. 2; and cf. Lossen: Erläut. zur. geol. Specialkarte von Preussen, Blatt Harzgerode, 1882, p. 81; and Williams' Bull. U. S. Geol. Survey, No. 28, Pl. I, fig. 2; Pl. II, fig. 1, 1886.
[2] cf. H. Credner: Neues Jahrbuch für Mineral., 1870, p. 972.

Biotite originates under certain circumstances from hornblende. This is an alteration well known to mineralogists,[1] and may be admirably seen in several of the Horse Race diorites and in the curious amphibole granite, No. 11831, figured in Pl. XVI, fig. 2.

Muscovite, Sericite.—The potash micas hold a similar place in relation to orthoclase, as a product of dynamic metamorphism, that saussurite does to the lime-soda feldspars. In some specimens, as for instance in the granite No. 11089 from the Horse Race and in No. 11660 from the so-called gold mine near Pine street, Marquette, broad plates of typical muscovite are developed in the feldspar; generally, however, the alteration is due to the minute scales or curved foliæ called sericite. These two minerals are quite identical in composition and generally in origin, as has been explained in Chap. I. The development of sericite may be best studied in the schistose porphyries, which owe their cleavage to stretching. These are abundant in both the regions investigated, especially at Upper Quinnesec Falls (see Chap. III, and Pl. XIV, fig. 1) and near the city of Marquette (Chap. IV). While the production of sericite in the acid rocks is for the most part the result of intense dynamic action, it would seem as though it were especially liable to result, like certain varieties of chlorite (see below), when this force acted as a tension rather than as a compression.

Titanium minerals.—The metamorphosed eruptive rocks of the regions studied offer unusual opportunities for tracing the varied transformations of the titanium compounds. It is doubtful whether this element existed in the original rocks in any other form than titanic iron (ilmenite) or as a component of certain biotites. In the metamorphic rocks, however, titanium minerals are numerous and their origin can be traced to different sources. The probable derivation of rutile and magnetite from ilmenite may be seen in No. 11070, from Upper Quinnesec Falls (Pl. XIII, fig. 2), and also in No. 11825, from northwest of Marquette (p. 184). The little "Thonschiefernadeln," shown in Fig. 12 (p. 106), seem also to have been derived from ilmenites. A sagenitic network of rutile produced by the alteration of biotite and the consequent freeing of titanic oxide is seen in No. 11113, from Iron Mountain; in No. 11672 from Marquette; and in No. 11738, from near Baldwin's Kilns, Negaunee.

Anatase, along with leucoxene, has resulted from the alteration of ilmenite in No. 11130, from Twin Falls (Fig. 26, p. 166) and in No. 11802, north of Negaunee, near the Carp River. Anatase seems also to have resulted from the decompositon of titaniferous biotite in Nos. 11050 and 11052, from near Upper Quinnesec Falls.

Sphene in the form of leucoxene is a universal result of the alteration of ilmenite in the metamorphosed diabases. In rare cases, like No. 11014, from Lower Quinnesec Falls, it is intimately associated with

[1] See J. Roth: Allgemeine undchemische Geologie, vol. 1, p. 333, 1879, and Inostranzeff: Metamorphosirte Gesteine im Gouvernment Olonez, 1879, p. 192.

rutile, which may have been produced simultaneously with the alteration of the leucoxene, or have resulted from it. In other exceptional cases the product of the ilmenite appears with all the crystal form and physical properties of rock-forming sphene. Such an occurrence in No. 11189 from the Horse Race is shown in Pl. XIII, fig. 1; and another in No. 11831, from northwest of Marquette, in Pl. XVI, fig. 2.

The secondary minerals thus far enumerated are products of metamorphism proper, as distinguished from weathering; that is, they are highly crystalline, and have been produced under circumstances very different from those ordinarily prevailing at the earth's surface. Here the tendency is for the more crystalline and less soluble compounds to become more soluble through union with water and carbon dioxide. Hydration and carbonatization are therefore characteristic results of surface action upon rocks. They bring about their disintegration and decay, as purely metamorphic processes do not. Both metamorphism and weathering are very apparent in the eruptive masses of the Menominee and Marquette regions. The rocks of Keweenaw Point, on the other hand, show only the effects of weathering. In spite of their great antiquity they have not undergone metamorphism in the strict sense. Much younger rocks in disturbed areas are often found to be intensely metamorphosed, which clearly shows that something besides mere lapse of time is necessary to accomplish this change.[1]

PRODUCTS OF WEATHERING.

The secondary minerals in the Menominee and Marquette massive rocks which owe their existence to atmospheric action or weathering belong mainly to the following species: Chlorite, talc, serpentine, carbonates (calcite, dolomite, etc.), iron-hydroxide, and pyrite.

Chlorite is generally a product of weathering, but its origin is sometimes closely associated with dynamic agencies. For instance, it is a constant feature in the basic rocks which have been stretched (like sericite in the more acid ones), filling with its parallel folia the interstices between the broken and separated fragments, and thus imparting a degree of schistosity to the entire mass. (see Pl. XI, fig. 2.) The ordinary process of chloritization has been described in Chapter I, and frequently alluded to in the petrographical descriptions, since it is extremely common in the basic eruptives. If the original mineral was very poor in iron an almost colorless chlorite was the result, as in the Sturgeon Falls gabbro (Pl. VIII, fig. 2). In the highly ferruginous diabases, on the other hand, the chlorite has a deep green color and is often pleochroic. This is the "viridite" of the older authors, which is

[1] The efficiency of orographic movements to bring about this result has already been sufficiently emphasized. The observations of Lossen that similar changes may be produced by the contact action of large masses of intrusive granite have been briefly referred to in Chapter I. To what extent the enormous granite areas lying on both sides of the Marquette and Menominee greenstone belts may have been instrumental in effecting their mineralogical metamorphism must for the present be left undecided, inasmuch as no evidence directly bearing upon this question has as yet been collected.

frequently associated with sharply defined epidote (secondary augite of Wichmann), as figured in Pl. XI, fig. 1. Chlorite seems to be the common effect of weathering upon pyroxene, hornblende, and biotite.

The peculiar variety of chlorite known as "helminth" in vermiform aggregates occurs imbedded in secondary quartz in some of the Sturgeon Falls gabbros, and is represented in Fig. 8 on p. 71.

Talc results in some cases from the alteration of hornblende, as observed by Tschermak,[1] Inostranzeff,[2] Becke,[3] and the writer.[4] This is not a common phenomenon in the Michigan greenstones, but some admirable examples were observed in the coarse grained diorites of the Horse Race above Upper Quinnesec Falls.

Serpentine.—The scarcity of olivine in the rocks examined makes the ordinary derivation of serpentine uncommon. This, however, does occur in some of the least altered diabases of Marquette. Indeed, serpentinization is almost the only effect of weathering noticeable in some specimens from the great dike of Lighthouse Point (olivine diabase), certain weakly polarizing fibers resulting from the change of hornblende appear to be serpentine, which, according to Rosenbusch,[5] frequently gives rise to this mineral. An instance of this may be seen in Nos. 11078 and 11191 from the Horse Race (p. 109).

Carbonates.—These most frequent products of weathering abound in the most altered greenstones, but they are nevertheless not unfrequently absent on account of the readiness with which these compounds are removed in solution. Calcite and dolomite are not microscopically distinguishable without a chemical reaction, but this is hardly necessary for most cases.

Iron-hydroxide and *Pyrite* are both iron compounds universally produced in basic rocks under ordinary atmospheric influences. The Michigan greenstones present no exception in the amount of these minerals which they contain.

PROGRESS OF ALTERATION IN THE ORIGINAL MINERALS.

Feldspar gives alteration products depending very largely upon its original composition, whether alkaline or calciferous. By far the most common change in the more basic rocks is to saussurite. This varies in different cases from a comparatively coarse grained zoisite aggregate to a dull gray, almost opaque mass which, even in the thinnest sections, is beyond the highest power of the microscope completely to resolve. The saussuritization may be often seen to have proceeded from the periphery of the feldspar crystal inward. In such cases a comparatively unaltered center remains, as in No. 11168 from Sturgeon Falls (Pl. VIII, fig. 2). Quite as frequent is the occurrence of a clear per-

[1] Tschermak's mineral. u. petrog. Mittheil., vol. 4, p. 65, 1876.
[2] Metamorphosirte Gesteine im Gouvernment Olonez, Leipzig, 1879, p. 167.
[3] Tschermak's mineral. u. petrog. Mittheil., vol. 4, 1882, pp. 339 and 349.
[4] Bull. U. S. Geol. Survey, No. 28, p. 58, 1886.
[5] Mikros. Physiog., 2d ed., vol. 2, p. 108.

iphery around feldspar crystals which have been completely saussuritized. (See No. 11167 from Sturgeon Falls (Pl. VIII, fig. 1); No. 11054 from Upper Quinnesec Falls, and No. 11182 from the Horse Race.) The clear feldspar substance in such cases appears like a new crystallization rather than an unaltered survival of the original individual (cf. Fig. 4, p. 69).

The inverse ratio existing between the mechanical and the chemical action visible in the altered feldspars of the basic rocks has been often alluded to on pp. 88, 169. This seems to be the reverse of what might be expected, as well as of what is actually observed in the case of all the other constituents. It is, however, frequently the fact that, in a continuous rock mass, feldspar is most completely saussuritized which occurs in the least crushed portion, while the rock which is most broken, stretched, and foliated retains its feldspar fragments in a quite fresh and unaltered condition. That this fresh feldspar is not a new crystallization, is proved by the fact that fragments can often be seen to have once fitted together, as portions of one individual, before the crushing took place. Among many sections in which this phenomenon can be observed may be mentioned: The Sturgeon Falls gabbro; the rocks of the diorite ridge near the Lower Quinnesec Falls; Nos. 11004, 11010, 11019, and 11102 from just below the Lower Quinnesec Falls; Nos. 11054, 11073, and 11056 (see Fig. 11) from Upper Quinnesec Falls; No. 11179 from Four-Foot Falls, and Nos. 11651 and 11652 from the Cleveland ore dock in Marquette.

Such observations, made at many widely separated localities within the Menominee and Marquette greenstone areas, would at first thought seem to indicate that there is a reciprocal relation between the chemical and mechanical effects produced by great pressure. In other words, that the force which in the massive portion of the rock caused increased chemical action and alteration of the feldspar to saussurite, was expended, in another part, in the work of crushing. The fact, however, that the bisilicate constituents are more altered in the crushed bands than in the other part of the rockmass is opposed to such an explanation, and seems rather to indicate that the more ready alteration of these and the production of such minerals as fibrous hornblende, chlorite, and talc, formed a soft matrix which protected the feldspar from the further action of pressure and chemical action.

A totally different alteration from saussuritization is sometimes observed in the feldspars of the more basic eruptives. This consists of their change to green hornblende needles, and can of course occur only where a portion of the necessary elements is furnished by some bisilicate. These elements (i. e., magnesium and iron) wander along the cleavage cracks of the feldspar, causing the development of the needles as shown in Pl. XII, fig. 2. A very complete instance of this change is shown in the epidiorite, No. 11663, from Pine street, Marquette.

Still another alteration of the plagioclase is to epidote. This is com-

plete in No. 11091 from the Horse Race, and partial in No. 11712 from the Brook Section, near Marquette.

While the lime feldspars change to zoisite, epidote, or hornblende, the alkaline feldspars show a corresponding tendency to pass into mica (sericite). This process is most commonly central, the periphery of a crystal remaining intact after the interior is completely altered, as may be seen in No. 11104, the granite from south of Upper Quinnesec Falls. This same specimen exhibits an interesting phase of the inverse ratio existing between the mechanical and the chemical action in the acid feldspar. Microcline seems to have been abundantly developed from orthoclase by pressure but while the orthoclase itself is sericitized, *the microcline never shows a trace of this change.*

Pyroxene is comparatively rare in the rocks studied, occurring only as diallage in the Sturgeon Falls gabbro, and as augite in the younger Marquette diabases; nevertheless, from the structure of many of the other rocks, we may affirm with certainty that they once contained pyroxene, and may hence trace the alterations which this mineral has undergone.

The most common, and indeed the almost universal change of the pyroxene in the Menominee and Marquette rocks is to hornblende. The compact brown hornblende in the Sturgeon Falls gabbro and in the porphyritic rocks from the west end of the ridge near Lower Quinnesec Falls, shows strong evidence of having originated from pyroxene, but this can not perhaps be regarded as beyond all doubt. Compact green hornblende appears to replace original diallage in the gabbro-like diorite which forms the barrier rock at Upper Quinnesec Falls (see Pl. X, fig. 1), where it even retains the orthopinacoidal parting. The same mineral likewise seems to replace original augite in many of the Horse Race diorites, whose structure is typically diabasic.

Fibrous green hornblende or uralite is too common and well known an alteration product of pyroxene to deserve especial description. It is universally distributed through all of the more basic rocks in the areas investigated.

A colorless chlorite may be seen originating from the almost colorless diallage of the Sturgeon Falls gabbro, as shown in Pl. VIII, fig. 2. From the varieties of pyroxene which are richer in iron, a deep green chlorite results which is often associated with epidote, as shown in Pl. XI, fig. 1.

Hornblende.—Without reference to the original or secondary origin of the hornblende itself, this mineral is found subject to several different alterations.

It passes from the compact to the fibrous form by fraying out at the ends, as shown in specimen No. 11175, from the Four-Foot Fall (see Fig. 19, p. 126). It also seems to give rise to biotite in many of the Horse Race diorites and in the amphibole granite, No. 11831, obtained at the camp northwest of Marquette. (See Pl. XVI. fig. 2.) Talc

frequently is produced by hornblende alteration in the Horse Race diorites as described in Chap. III (p. 107). A colorless chlorite, closely resembling that produced from the Sturgeon Falls diallage, is derived from the pale hornblende (itself probably paramorphic) of No. 11098, from the ridge near Lower Quinnesec Falls. This is produced in spots over the hornblende and is visible only by its isotropic behavior in polarized light, as shown in Fig. 9 (p. 79). The viridite (chlorite) epidote aggregate originates from hornblende just as it does from pyroxene. Finally serpentine is an exceptional result of hornblende alteration, as may be seen in specimens 11078 and 11191 from the Horse Race (p. 109).

Biotite shows the usual alterations and is principally the result of weathering rather than of metamorphic processes. Bleaching first takes place and then chloritization. Carbonates are sometimes separated in the form of interpolated lenses, while the titanium which entered into their composition separates out sometimes as anatase (Nos. 11050 and 11052 from Upper Quinnesec Falls) and sometimes as rutile.[1] (Nos. 11113, from near Iron Mountain in the Menominee valley, No. 11672 from Marquette and No. 11738 from the Brook Section.)

Olivine occurs only in a few of the Marquette diabases, where its alteration is the usual one to serpentine.

Ilmenite is the last of the important original constituents of the Menominee and Marquette massive rocks whose alterations can be clearly traced. This gives rise to a variety of new titanium minerals

Its commonest change is that to leucoxene, which is everywhere encountered, see Pl. IX, figs. 1 and 2.

Sphene or titanite, of which leucoxene is only a special form, sometimes originates from ilmenite, as is shown in Pl. XIII, fig. 1, and in Pl. XVI, fig. 2.

Anatase also, in association with leucoxene, is a secondary product of ilmenite alteration. This is shown in Fig. 25 (p. 131) of No. 11130, from Twin Falls, as well as in No. 11802, one of the stretched agglomerates on the Carp River. (See Chap. V, p. 177.)

[1] On the frequency of these changes see Whitman Cross: "Petrography of the Leadville Rocks" in Mon. U. S. Geol. Survey, vol. 12, 1887.

PLATES.

PLATES.

PLATE VIII.

PLATE VIII.

FIG. 1.—*Saussurite gabbro* (*first stage*).

From point *h*, Pl. III, at Sturgeon Falls, Menominee River, Michigan. Specimen No. 11167*a*. Ordinary light. (See p. 68.)

The triclinic feldspar, which shows occasional idiomorphic forms indicating that it is in part, at least, older than the pyroxene, here appears almost completely altered to an opaque, gray saussurite. A high magnifying power resolves this into an aggregate of minute zoisite needles, calcite and albite. These are somewhat unevenly distributed which produces the blotched appearance of the saussurite.

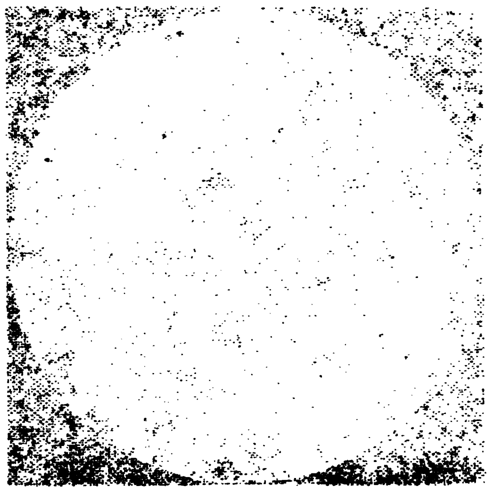
The diallage, which is of a pale green color in the hand-specimen, is almost colorless when seen under the microscope. Its well marked orthopinacoidal parting is seen on the right of the figure. This diallage is surrounded by a border of compact hornblende, which is either brown, pale green or colorless. It frequently becomes fibrous on its exterior edge, as is shown in Fig. 7, on p. 70. Small patches of compact brown hornblende are also abundantly scattered over the entire surface of the diallage in a manner that would seem to indicate that it had originated from the latter by paramorphism. There is some pale green chlorite visible in the upper part of the drawing and on the right is a bit of ilmenite and leucoxene.

FIG. 2.—*Saussurite gabbro* (*second stage*).

From point *f*, Pl. III, at Sturgeon Falls, Menominee River, Michigan. Specimen No. 11154. Represented between crossed nicol prisms. (See p. 72.)

A large individual of the pale diallage is here seen in an advanced stage of alteration to a colorless chlorite. Because of the almost isotropic character of this mineral, it is necessary to show its appearance in polarized light. Imbedded in the chlorite are remnants of the still brightly polarizing diallage, and around it is the border of hornblende, which here shows pale yellow interference colors.

The feldspar is less completely saussuritized than in the last figure. Its characteristic twinning lamellæ are still visible in many instances, particularly at the center of the crystals.



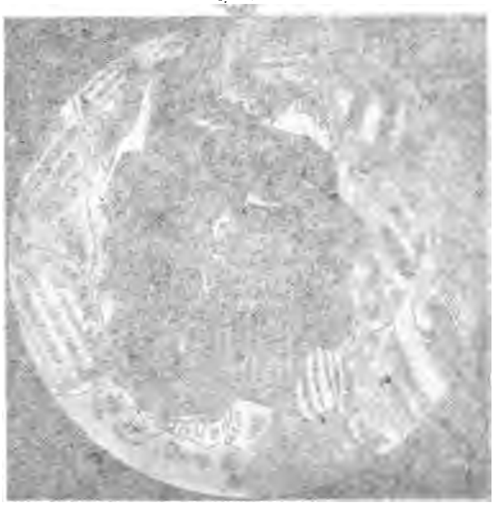


FIG. 2 X30

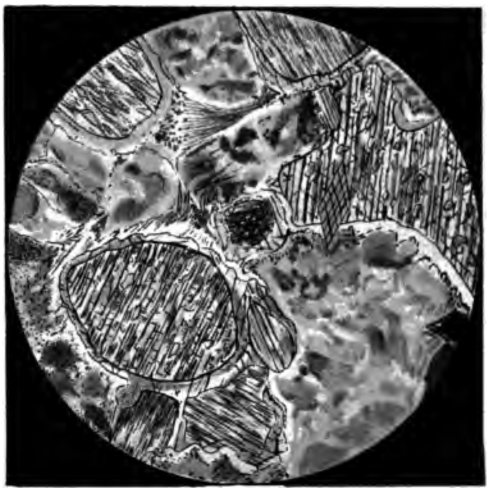


FIG. 1 (X30)

FIG. 2 (X30)

G.H.W. DEL.

PLATE IX.

PLATE IX.

FIG. 1.—*Altered diabase or diorite.*

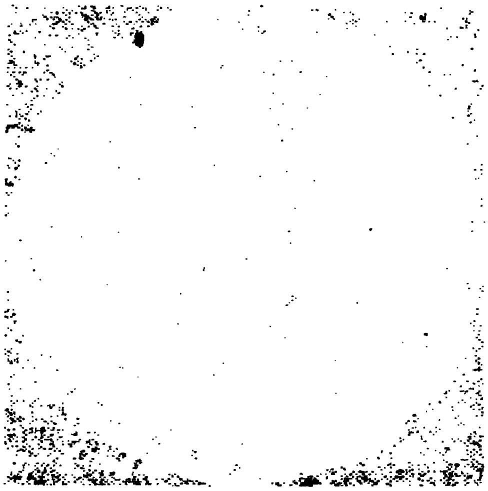
From the so-called "Gabbro Ridge," below Lower Quinnesec Falls, Menominee River, Michigan. Specimen No. 11028. Ordinary light. (See p. 81.)

The original structure of this rock has been completely changed, in spite of its still massive character. It is now composed of pale green, fibrous hornblende, saussurite, quartz, calcite, chlorite, ilmenite, and leucoxene. Most of these constituents are of secondary origin, and in the process of their formation the form of the primitive minerals has been so completely obliterated that it is now impossible to say whether the mother-rock was a diabase or a diorite.

FIG. 2.—*Schistose band in the last figured rock, showing the effect of dynamic metamorphism (stretching) upon it.*

Locality same as that of last figure. Specimen No. 11031. Ordinary light. (See p. 82.)

The feldspar in this rock is chemically less altered than in the last, but it has been subjected to a much more intense mechanical action. It is fractured, and the fragments are widely separated, although those pieces which once belonged to the same crystal may still often be identified. The interstices are filled with scales of a green chlorite, arranged parallel to one another, so as to produce a schistose structure. Even the little leucoxene zones around the ilmenite grains have been elongated in the same direction.



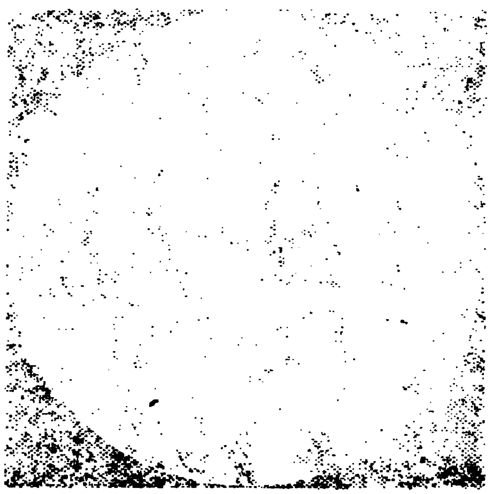


FIG. 1 (X80)

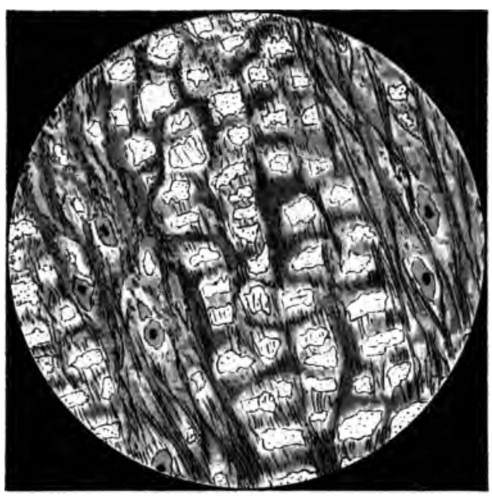


FIG. 2 (X80)

G.H.W. DEL.

PLATE X.

PLATE X.

FIG. 1.—*Saussurite diorite.*

This rock forms the barrier at Upper Quinnesec Falls, Menominee River, Michigan. Specimen No. 11054. Ordinary light. (See p. 103.)

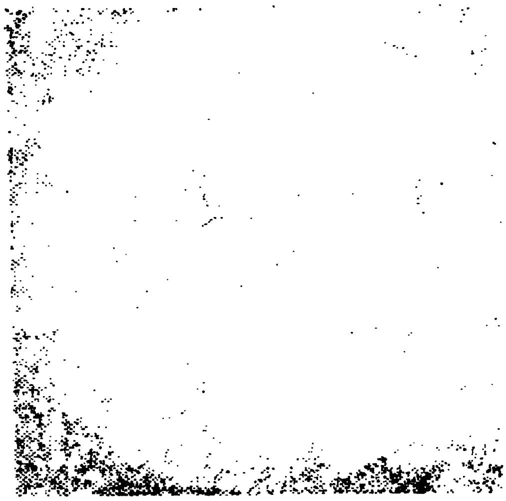
In spite of the close external resemblance of this rock to the Sturgeon Falls saussurite gabbro (Pl. VIII, fig. 1), it shows no trace of any pyroxenic constituent. Its only bisilicate is hornblende. This is sometimes compact (and then both brown and green in color), sometimes ragged and fibrous. The former variety is seen in the center and on the left of the figure, with its remarkably perfect orthopinacoidal parting, like that recently observed by Cathrein in a hornblende from Roda, in the Tyrol. This parting may be an indication that this hornblende has been derived from original diallage. A large individual of the more ragged and fibrous hornblende, filled with secondary quartz, is shown on the right of the figure.

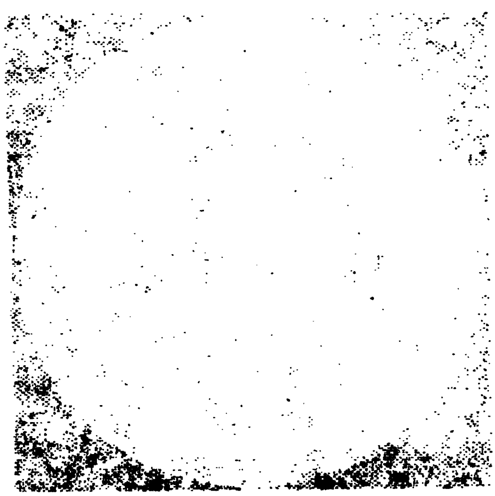
The feldspar of this rock has undergone the usual alteration to opaque, gray saussurite, but in this are imbedded frequent grains of a fresh brown feldspar. Leucoxene rims around the ilmenite are abundant.

FIG. 2.—*Typical aphanitic greenstone of the Marquette region.*

From Baldwin's Kilns, northeast of Negaunee, Michigan. Specimen No. 11747. Ordinary light. (See p. 172.)

This is a fair representative of the commonest rock type in the southern Marquette and Negaunee greenstone areas. Its grain must always have been very fine and compact. Long, slender feldspar crystals may still be seen, sometimes with an imperfectly developed form, such as is common in the semi-crystalline rocks (porphyrites). The groundmass is composed of a fine grained aggregate of fibrous hornblende, chlorite, quartz, calcite, and ilmenite leucoxene. These minerals are all secondary, and may easily have resulted from the alteration of a cryptocrystalline, or even a partially vitreous base.





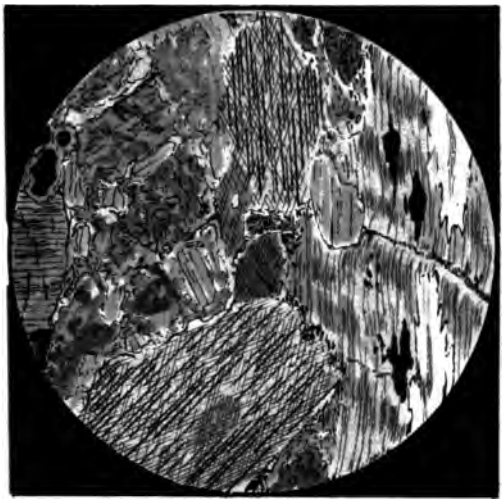


FIG. 1 (X30)

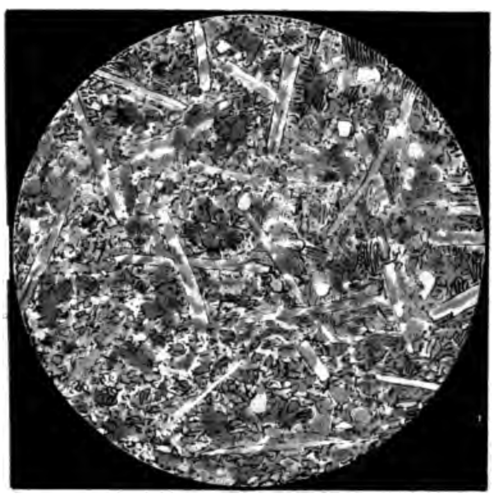


FIG. 2 (X110)

G. H. W. DEL.

PLATE XI.

PLATE XI.

FIG. 1.—*Chlorite-epidote aggregate in an altered diabase.*

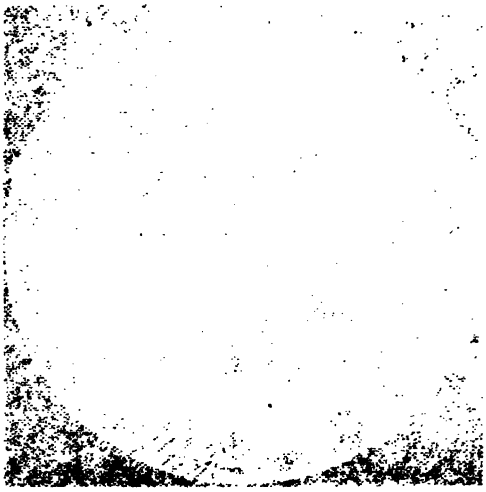
From below Upper Quinnesec Falls, Menominee River, Michigan. Specimen No. 11049. Ordinary light. (See p. 97.)

This is a very common alteration product in rocks of the diabase type, especially in those rich in iron. In a confused mass of deep green and somewhat pleochroic chlorite scales lie embedded extremely sharp crystals of a yellowish or colorless epidote. These latter are what the earlier students of these rocks mistook for secondary augite. In the lower part of the figure are seen ilmenite grains surrounded by rims of leucoxene and a portion of a large secondary hornblende crystal.

FIG. 2.—*Stretched greenstone.*

From above Lower Quinnesec Falls, Menominee River, Michigan. Specimen No. 11102. Ordinary light. (See p. 94.)

The effects of tension upon a solid rock mass are rarely seen more distinctly than in this specimen. Not only the feldspar, but also a large grain of ilmenite has here been forcibly torn asunder, and the fragments have been separated a considerable distance, always in one direction. The peculiar green chlorite so characteristic of all stretched basic rocks (cf. Pl. IX, fig. 2) fills the interstices between the mineral fragments. It must have crystallized after the breaking of the solid rock constituents and its scales, which are all arranged parallel to the direction in which the strain was exerted, produce a decidedly schistose structure in the rock. The fresh state of the feldspar in a rock which has been subjected to such intense mechanical action as this one is very noticeable.



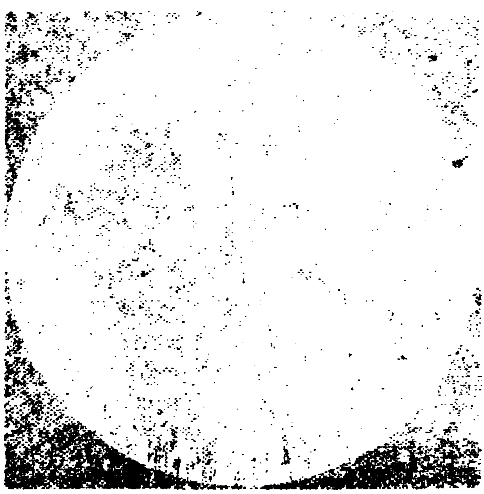


FIG. 1 (X180)

FIG. 2 (X30)

G.H.W. DEL.

PLATE XII.

PLATE XII.

FIG. 1.—*Coarsely crystalline diorite.*

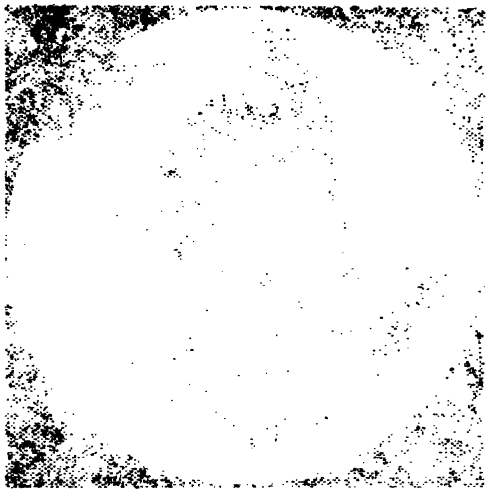
From near Baldwin's Kilns, northeast of Negaunee, Michigan. Specimen No. 11749. Ordinary light. (See p. 173.)

This one of the coarse grained dike rocks which penetrate the aphanitic greenstones of the Negaunee area. The hornblende is idiomorphic, and, as there are no certain traces of pyroxene, the rock is designated a "diorite." The feldspar is quite filled with secondary actinolite or epidote needles. The hornblende is often altered internally to chlorite or fibrous amphibole, while its exterior still remains compact and shows a curious concentration of the green coloring matter. There is also observable around the edge of the hornblende crystals a separation into fibers, as described by Becke.

FIG. 2.—*Epidiorite.*

From the Horse Race above Upper Quinnesec Falls, Menominee River, Michigan. Specimen No. 11186. Ordinary light. (See p. 107.)

This is one of the coarse grained dioritic rocks so abundant along the Horse Race Rapid. The pale green hornblende is entirely allotriomorphic and fills the spaces between the idiomorphic feldspar crystals exactly as augite does in diabase. Still there is no certain trace of pyroxene now present. The hornblende shows a deeper color around its edge and a breaking up into fibers, which are arranged in irregular bundles and appear to wander off into the surrounding feldspar.



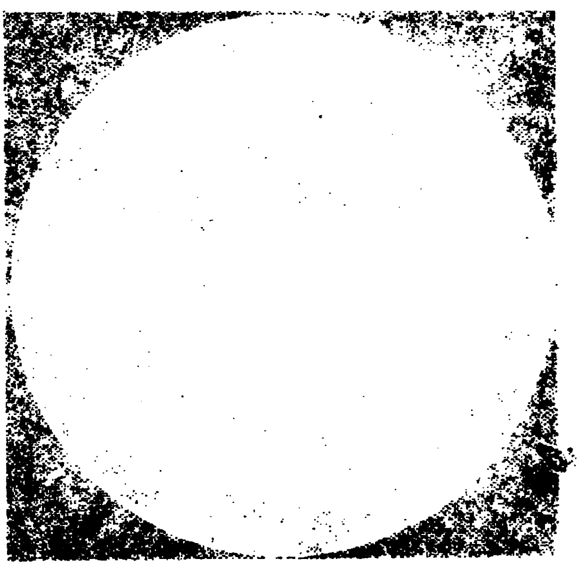


FIG. 1 (X 110)

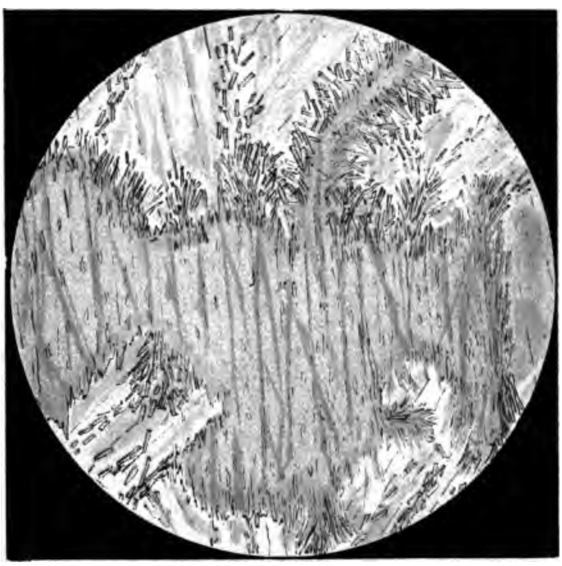


FIG. 2 (X 110)

G. H. W. DEL.

PLATE XIII.

PLATE XIII.

FIG. 1.—*Sphene crystals around ilmenite.*

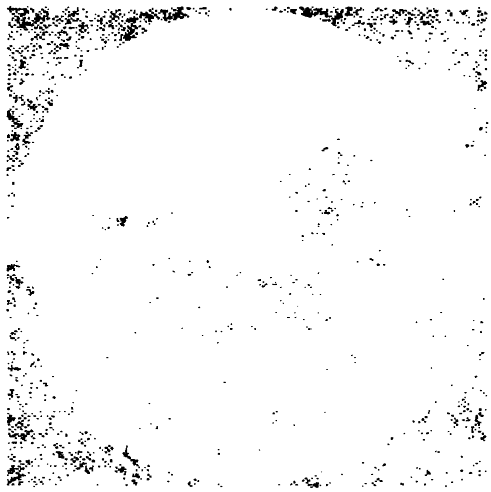
In a dioritic rock from the Horse Race Rapid, above Upper Quinnesec Falls, Menominee River, Michigan. Specimen No. 11189. Ordinary light. (See p. 109.)

These sphene crystals, although their minerological character is undoubted, are not so clear or so sharply defined as usual. They are gray and cloudy, resembling leucoxene in appearance; and, like this substance which is known to be identical with sphene in its composition, these crystals surround grains of ilmenite, as though they had originated from its alteration. If this be the case, we have here an interesting example of leucoxene assuming its characteristic titanite form.

FIG. 2.—*Rutile originating from the alteration of ilmenite.*

In a greenstone from below the Upper Quinnesec Falls, Menominee River, Michigan. Specimen No. 11070. Ordinary light. (See p. 99.)

The rock, which was probable once a diabase, now consists principally of green chlorite and reddish feldspar substance. The opaque iron oxide now present is magnetite. This occupies irregular areas and is intimately associated with a network of yellow rutile needles in a manner which renders probable the origin of both of these minerals from an original ilmenite.



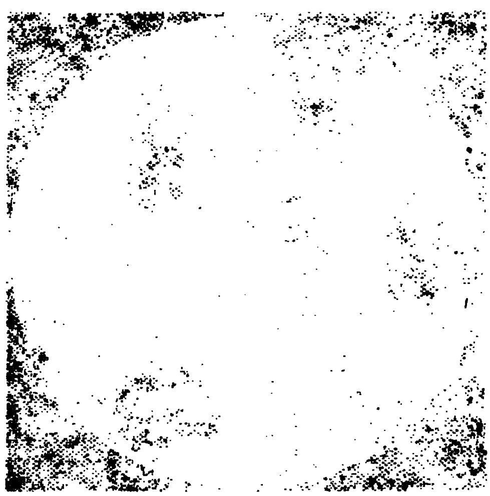


FIG. 1 (X80)

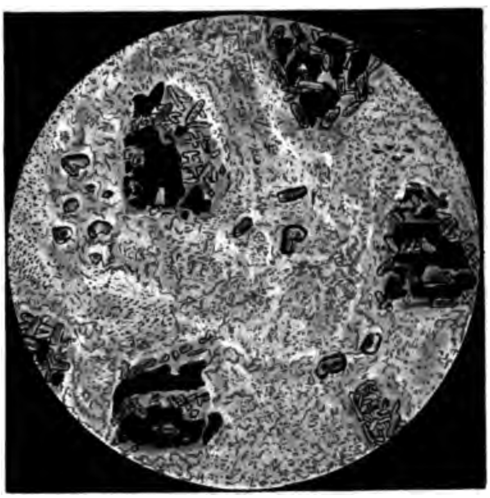


FIG. 2 (X110)

G. H. W. DEL.

PLATE XIV.

PLATE XIV.

FIG. 1.—*Sericite porphyry.*

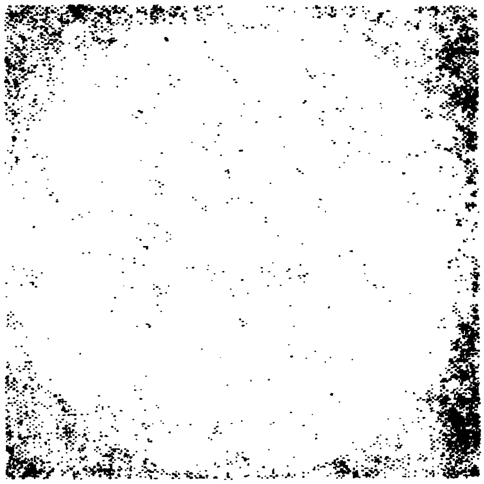
From just below the Upper Quinnesec Falls, Menominee River, Wisconsin. Specimen No. 11050. Nicols crossed. (See p.121.)

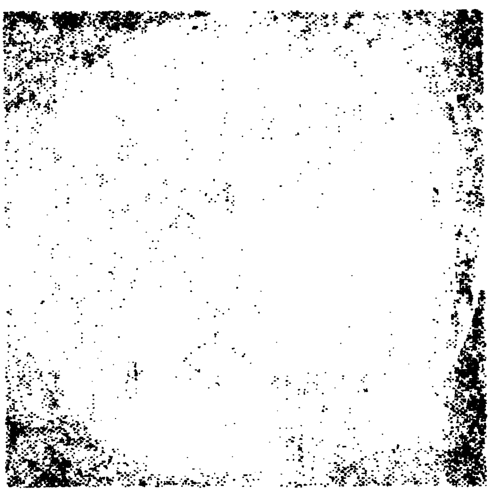
This rock, which was once an eruptive quartz porphyry, shows in an admirable manner the effect of stretching. The porphyritic quartz crystals are somewhat elongated and testify to the tension to which they have been subjected by an undulatory extinction. The porphyritic feldspar crystals are fractured and pulled apart always in the same direction, without reference to the position which they themselves occupied in the rock. The fissures are cemented by a new crystallization of sericite. The micrograniticgroundmass has been rendered schistose by stretching and by the abundant production of sericite, whose scales have a parallel arrangement.

FIG. 2.—*Stretched and brecciated greenstone.*

From near the Carp River, north of Teal Lake, Michigan. Specimen 11803. Nicols crossed. (See p.177.)

Some of the interstitial material, occurring between the massive cores of the spheroidally parted (brecciated) greenstones, contains distinct crystals of white feldspar. Between the eastern end of Teal Lake and the Carp River some of these massive cores are themselves much elongated by stretching. (See Fig. 27, p.177.) A section of the insterstitial material from this locality was selected for illustration because of the distinctness with which this stretching is apparent in the feldspar crystals. They are always broken and pulled apart in the same direction, while the smaller components of the rock show a corresponding elongation. The continuity of the original rock-structure in the interstitial portion of this exposure indicates that the spheroidal parting is in this case a result of cooling, rather than of mechanical brecciation in situ. (See p. 167.)





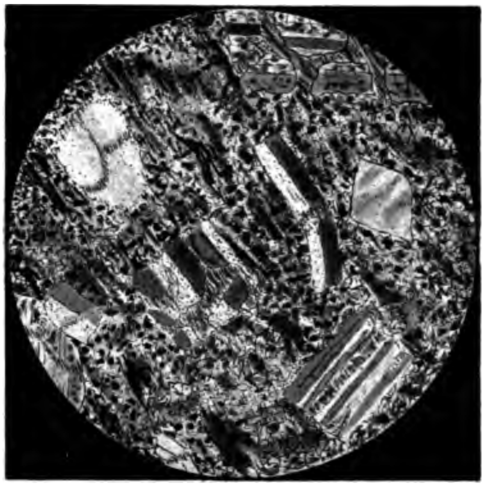


FIG. 1 (X30)

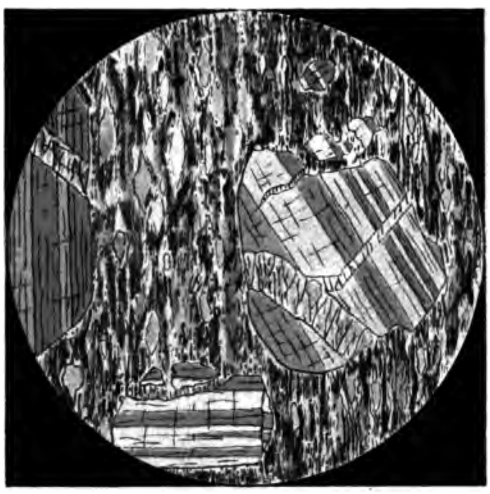


FIG. 2 (X30)

G. H. W. DEL.

PLATE XV.

PLATE XV.

FIG. 1.—*Structure of one of the "Augen" in an "Augengneiss," or stretched granite porphyry.*

From a schistose dike in the greenstones of the Horse Race Rapid above Upper Quinnesec Falls, Menominee River, Michigan. Specimen No. 11184. Ordinary light. (See p. 118.)

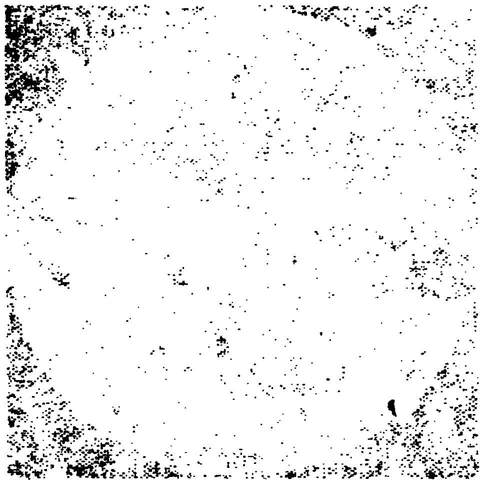
The center of the "Auge," or eye, is seen to consist of a portion of an old, brown colored porphyritic feldspar crystal. This is granulated on either side, and pulled out into a lens, whose longest axis agrees with the direction of the foliation. The granulation is composed of a new crystallization of the feldspar substance, which is clear, and although granitic in structure, it has a much coarser grain than the rest of the rock. This formation of an "Auge" out of a porphyritic feldspar crystal agrees with the observations of J. Lehmann, Chelius, and others.

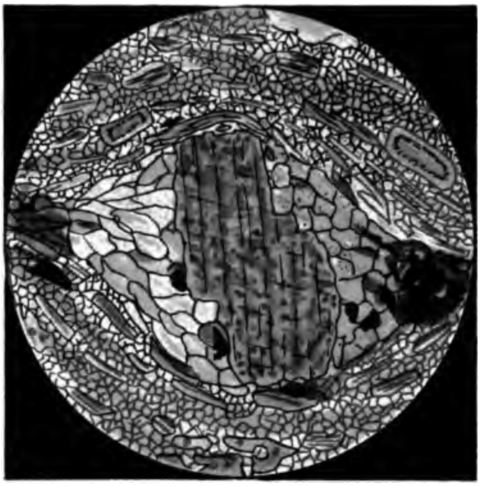
FIG. 2.—*Stretched quartz porphyry.*

From a conformable dike in the schistose greenstones of the Brook Section, west of Marquette, Mich. Specimen No. 11707. Nicols crossed. (See p. 150.)

This rock is particularly noticeable on account of the wonderful manner in which it shows the effects of a stretching action upon quartz. The original crystals are elongated into lenticular and pear shaped forms, or even into long, narrow bands. The first effect of the tension is to disturb the optical homogeneity and produce an undulatory extinction. If, however, the strain is great enough to overcome the force of cohesion, a mosaic of interlocking and differently orientated grains is the result. Similar phenomena have been observed and illustrated by J. Lehmann in Saxony. The porphyritic feldspar crystals in this rock are not broken, nor do they show the evidence of great pressure. Their form is generally intact, but it is worthy of remark that their center is always occupied by an irregular area of microcline.

The groundmass is finely microgranitic, containing sinuous bands of micaceous minerals, which bend around the porphyritic constituents, while they follow the general direction of the foliation.





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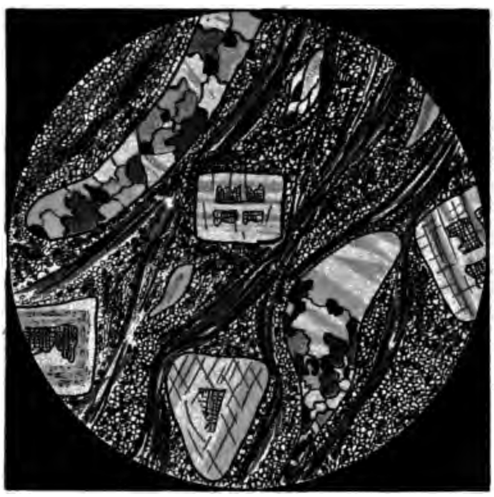


FIG. 2 (X30)

G. H. W. DEL.

PLATE XVI.

PLATE XVI.

FIG. 1.—*Greenstone schist (tuff) of the northern Marquette area.*

Lighthouse Point, Marquette, Mich. Specimen No. 11619. Ordinary light. (See p. 155.)

A characteristic, although by no means universal structure, in the banded green schists which compose so large a portion of the region around Marquette, consists in the tufted form of the hornblende crystals. These, although quite compact at their centers, are fibrous at the ends and expand so as to resemble sheaves tied in the middle. The fibers are so fine and the radial arrangement at the ends of the bundles is so perfect that the arm of a black cross is seen to sweep across the field when the thin section is viewed between crossed nicol-prisms. Hornblende with a structure like this has been observed by Renard and others as a new crystallization in altered sediments, a fact which lends additional support to the hypothesis that these green schists are tuff deposits.

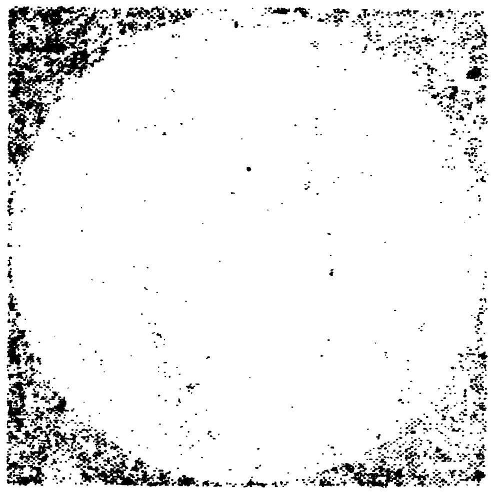
FIG. 2.—*Amphibole granite (?) forming a dike in aphanitic greenstones.*

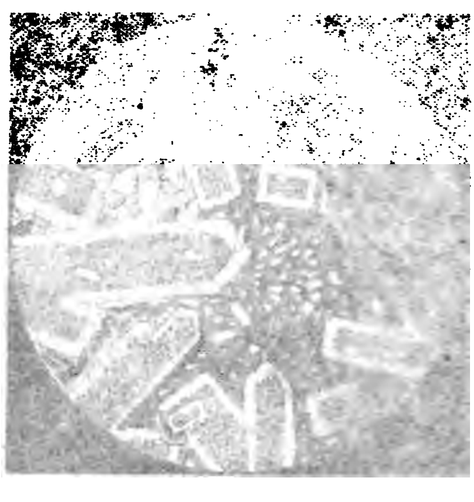
Northeast of Negaunee, Mich. Specimen No. 11831. Ordinary light in part; polarized light in part. (See p. 181.)

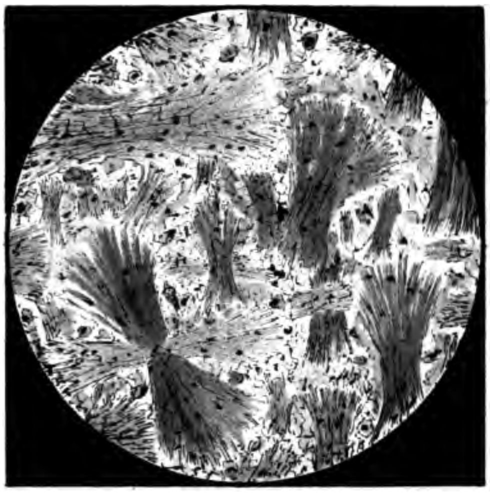
This rock presents many points of interest, both in its structure and alteration products. The feldspar is in two distinct generations, of which the older variety is entirely idiomorphic, with a zone of clear substance surrounding a gray and more altered interior.

The hornblende exhibits the unusual alteration to biotite, which is sometimes brown, sometimes green. This mineral in rare instances has crystallized in sharp hexagonal plates which show pressure lines of cleavage ("Drucklinien").

The groundmass of this rock is an aggregate of quartz and the younger generation of feldspar. These sometimes form a microgranitic mosaic and sometimes micropegmatitic growths, which are represented in the figure as they appear in polarized light. Apatite is abundant, and also ilmenite or magnetite surrounded by chlorite, and in some cases by sphene, as though this had resulted from the alteration of the ilmenite, as shown in Pl. XIII, fig. 1.







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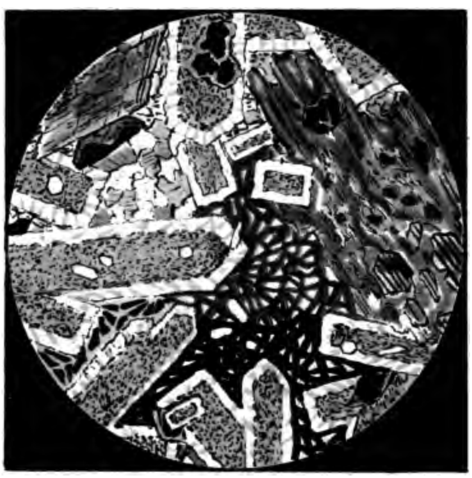

FIG. 2 (X30)

G.H.W. DEL.

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